UNIVERSITY OF WYOMING

BOMBARDIER
the evolution of mobility

NSU3D Results for the Second AIAA High Lift Prediction Workshop

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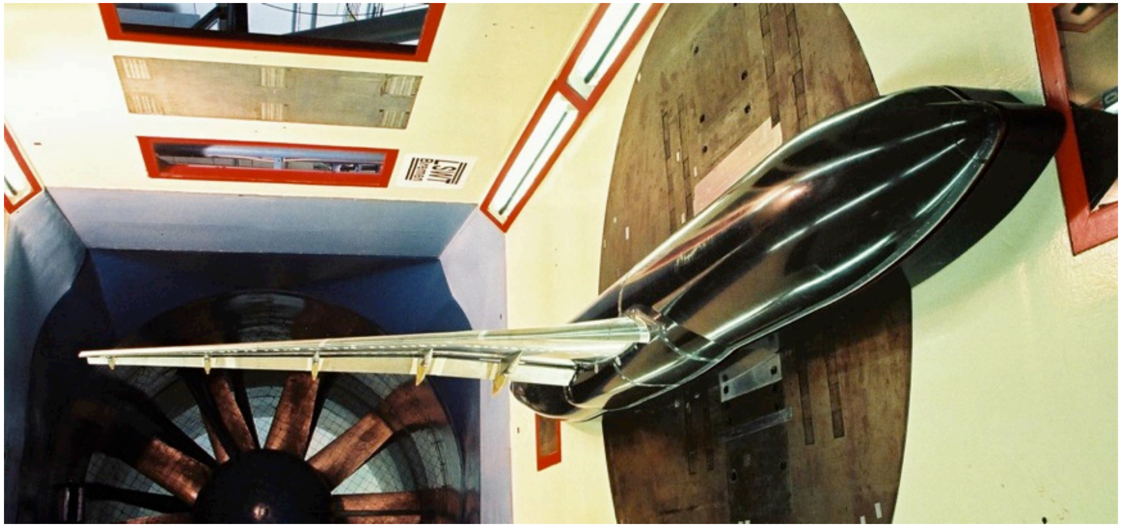
High-Lift Prediction Workshop 2

- Stated goals are to assess the state-of-the-art in CFD methods for simulations of high-lift configurations
- Provide a forum for exchange of ideas and practices related to this class of problems
- Continuation of the High-Lift Prediction Workshop 1

High-Lift Prediction Workshop 2

- Geometry definition for DLR F11
  - Full span slat deflected to 26.5°
  - Full span single-slotted flap deflected to 32°
  - AR of 9.353
  - $\Lambda_{c/4}$ of 30°
  - Γ of +4°



High-Lift Prediction Workshop 2

- Cases for the Workshop
  - Case 1
    - Grid convergence of simplified wing, slat, flap, and body configuration
  - Case 2
    - Alpha sweep at high and low Reynolds numbers of a wing, slat, flap, body, fairings and tracks configuration
  - Case 3
    - Alpha sweep of wing, slat, flap, body, fairings, tracks, and pressure tube bundles configuration

High-Lift Prediction Workshop 2 - UWyo and Bombardier Participation

- Uses NSU3D
- 2 grid types
  - VGRID
  - ICEM
- 2 turbulence models
  - S-A
  - K-ω
- Allows for comparison across models and grid creation methods

VGRID Meshes

- Workshop supplied meshes
  - Unstructured Merged Node Based (D)
  - Generated by Mike Long (UW) and Mark Chaffin (Cessna)
  - Follow gridding guidelines
  - Fully tetrahedral VGRID grids merged into mixed element meshes for NSU3D
- Prisms in boundary layer regions
- Total of 4 meshes used
  - C,M,F: Case 1
  - M: Case 2a and 2b

ICEM Meshes

- Generated internally at Bombardier Aerospace
  - Best practices for high lift
  - Generated using Ansys ICEM-Tetra/Prism mesh generator
  - Octree subdivision of domain that intersects geometry surface
- Surface mesh of isotropic triangles
- Prismatic layers grown in volume from surface triangulation
- Total of 4 meshes used
  - C,M,F: Case 1
  - M: Case 2a and 2b

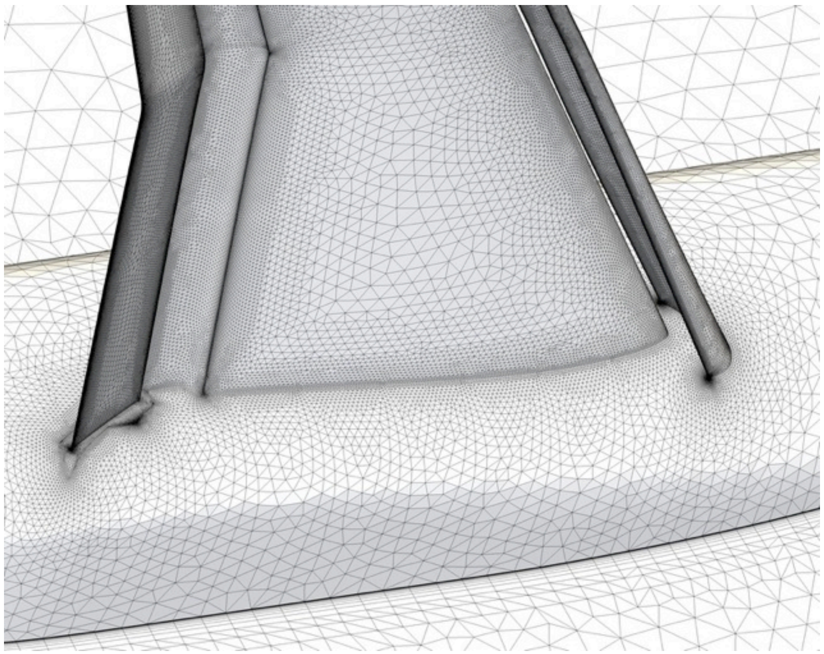
Grid Descriptions

VGRID						
Grid Name	**Nodes**	**Tetras**	**Prisms**	**First Cell Height**	**Growth Rate**	**Growth Factor**
Case 1 (Coarse)	10,229,072	13,820,586	15,395,027	5.5 e-04	1.15	0.02
Case 1 (Medium)	30,767,679	58,300,006	40,864,715	3.7 e-04	1.15	0.02
Case 1 (Fine)	75,978,568	186,999,490	86,668,878	3.7 e-04	1.15	0.02
Case 2	41,511,973	71,418,665	57,565,283	3.7 e-04	1.15	0.02

ICEM-TETRA					
Grid Name	**Nodes**	**Tetras**	**Prisms**	**First Cell Height**	**Growth Ratio**
Case 1 (Coarse)	17,477,000	10,083,000	30,953,000	5.5 e-04	1.085 – 1.8
Case 1 (Medium)	43,859,000	25,542,000	77,016,000	3.5 e-04	1.085 – 1.8
Case 1 (Fine)	121,407,000	85,978,000	208,056,000	2.4 e-04	1.085 – 1.8
Case 2	49,018,000	28,356,000	86,120,000	3.5 e-04	1.085 – 1.8

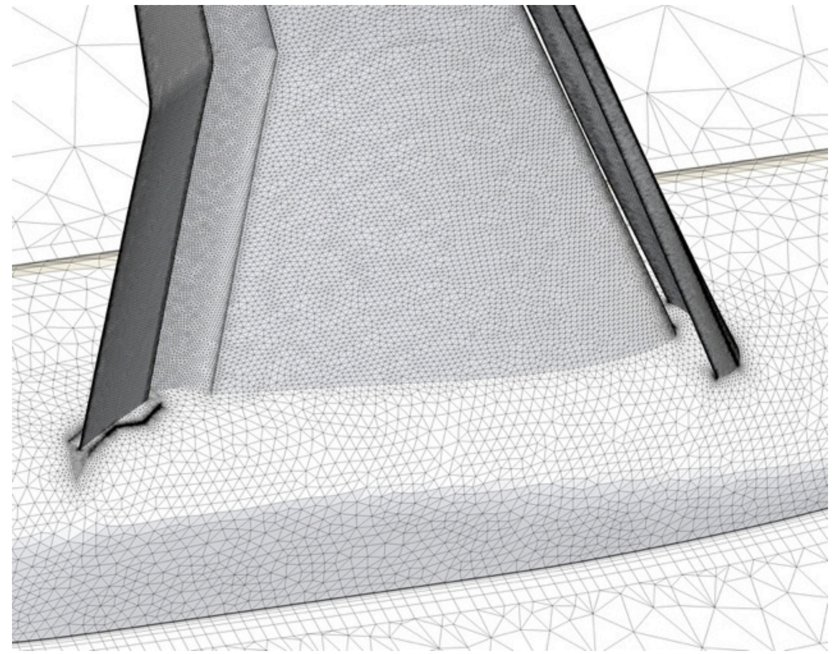
Case 1 Grid Description - Coarse

VGRID



- VGRID cells concentrated at edges
- Spanwise stretched surface cells
- Faster boundary layer growth rate
- Smoother transition into tetrahedra

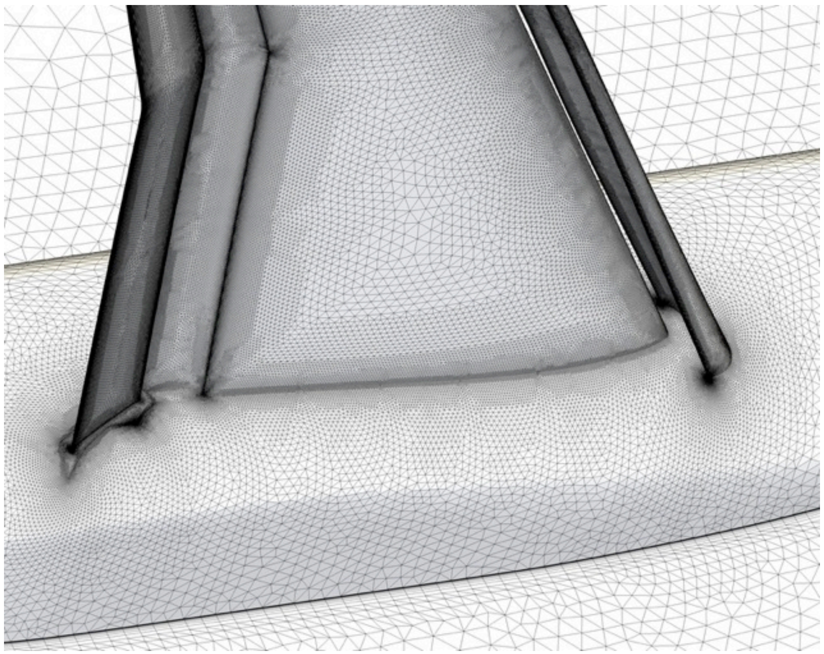
ICEM-TETRA



- ICEM has more even distributed cells across wall surfaces
- Isotropic surface cells
- Slower boundary layer growth rate

Case 1 Grid Description - Medium

VGRID



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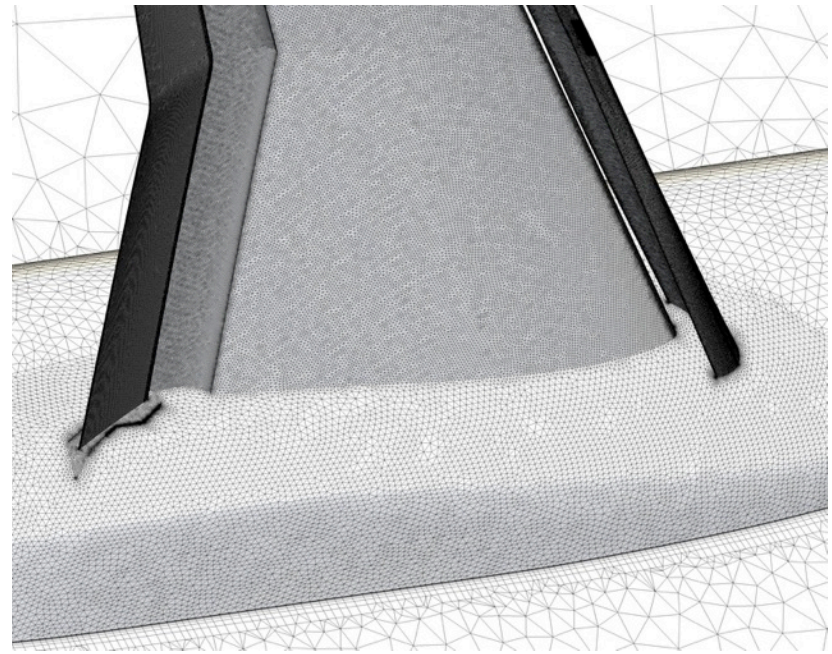
ICEM-TETRA



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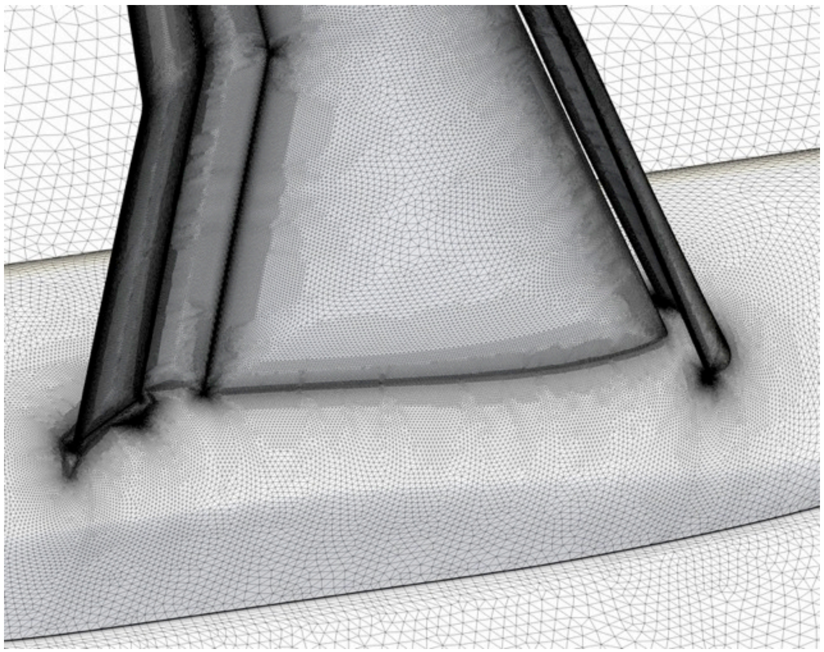
Case 1 Grid Description - Fine

VGRID



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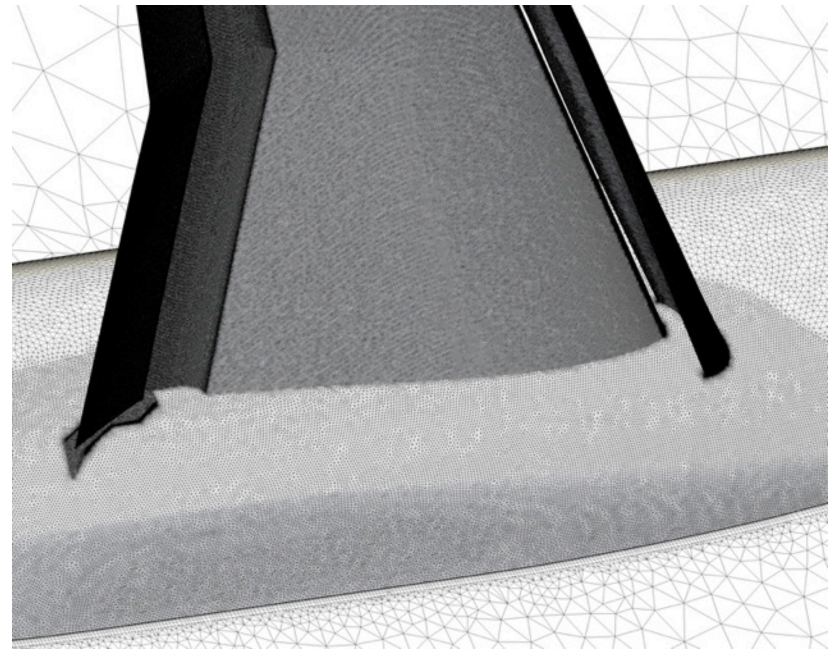
ICEM-TETRA



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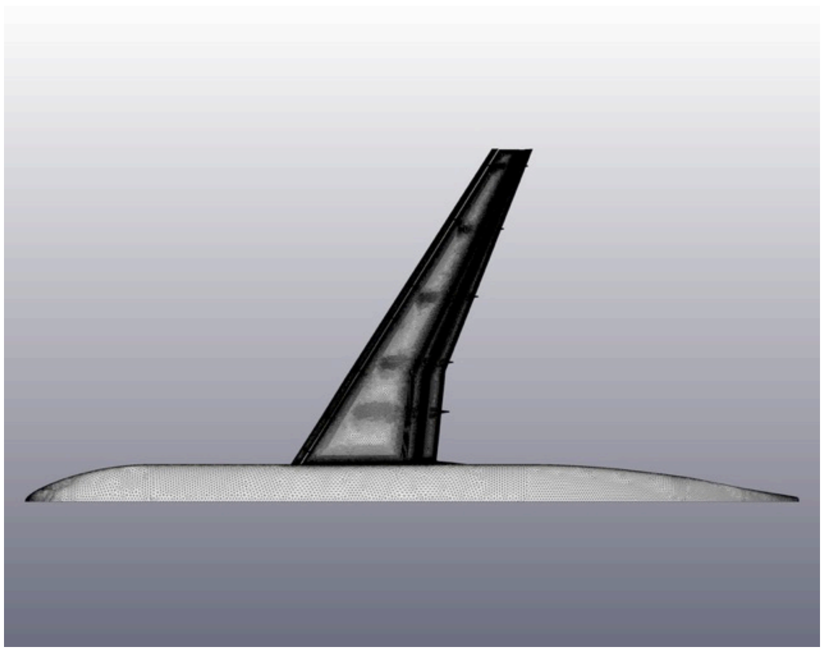
Case 2 Grid Description - Overhead

VGRID



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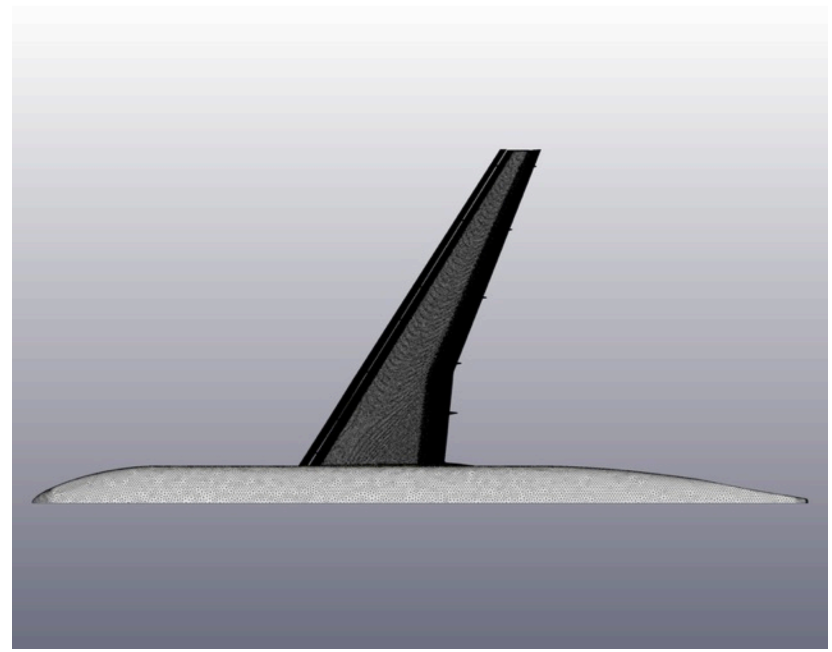
ICEM-TETRA



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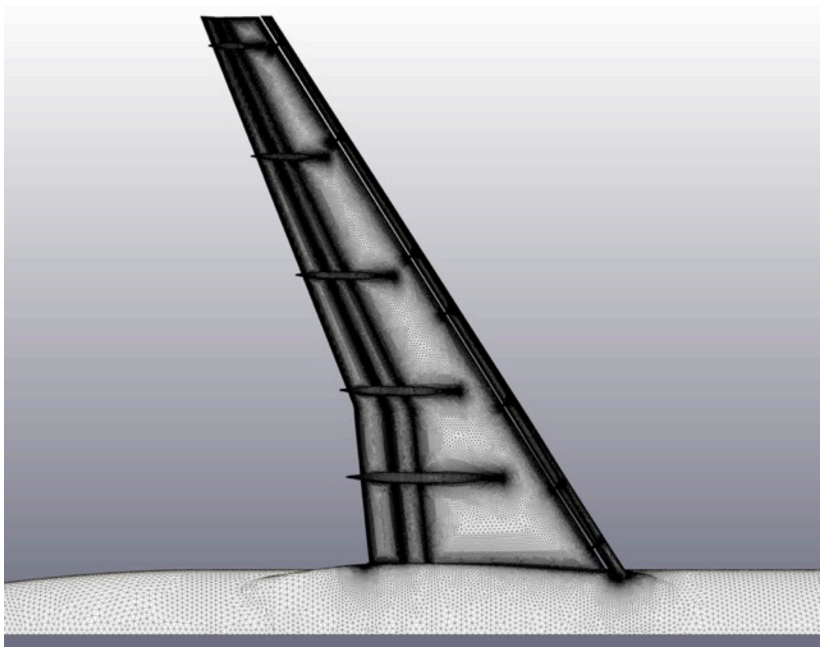
Case 2 Grid Description - Underside

VGRID



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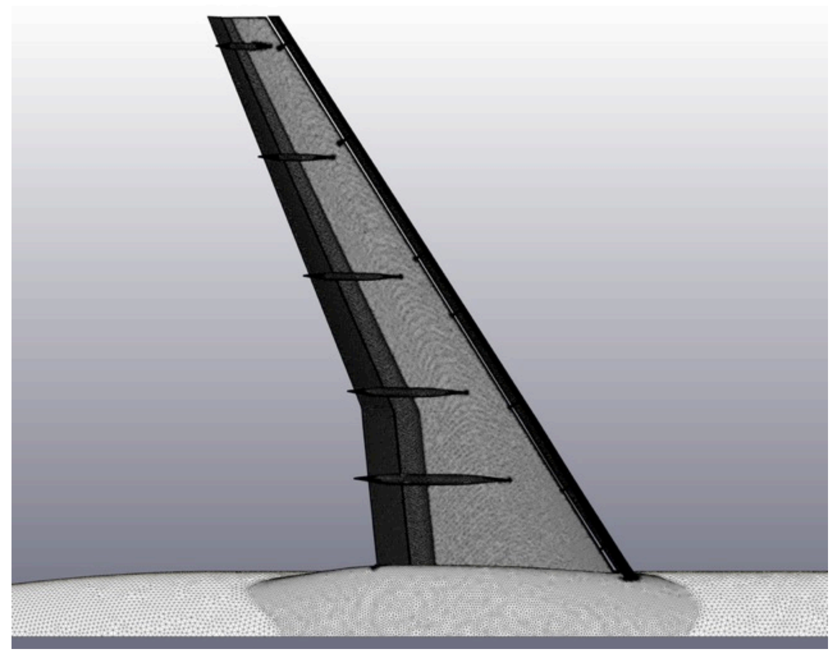
ICEM-TETRA



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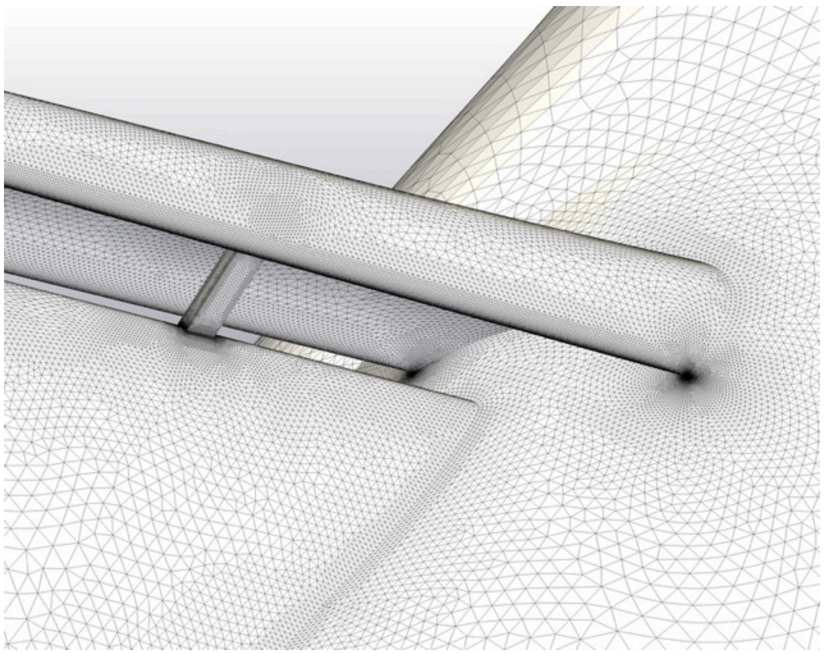
Case 2 Grid Description – Slat Inboard

VGRID



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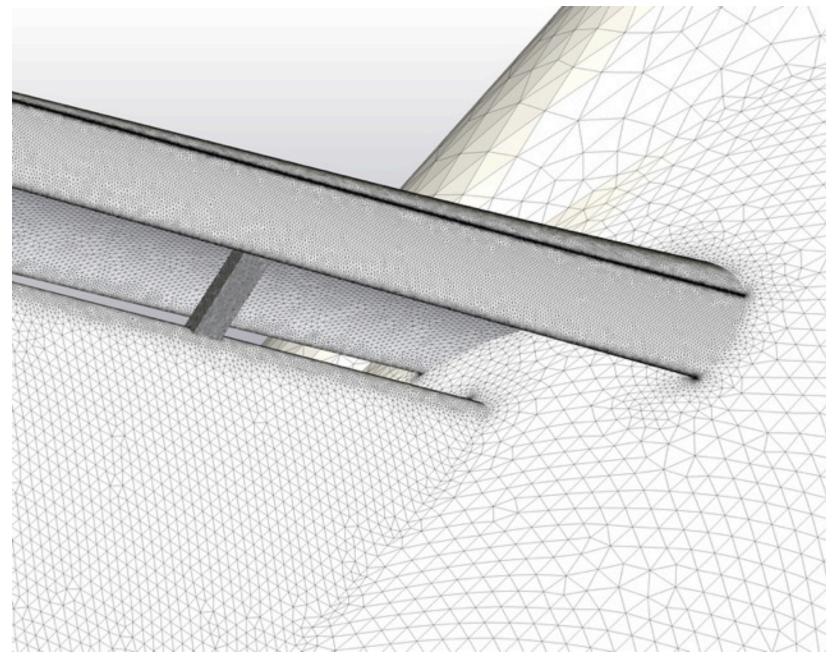
ICEM-TETRA



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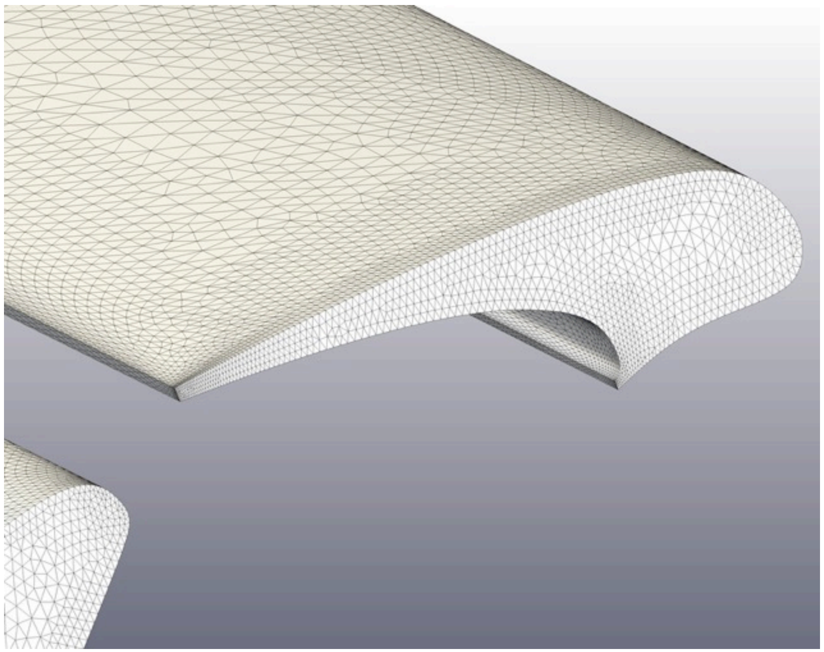
Case 2 Grid Description – Slat Outboard

VGRID



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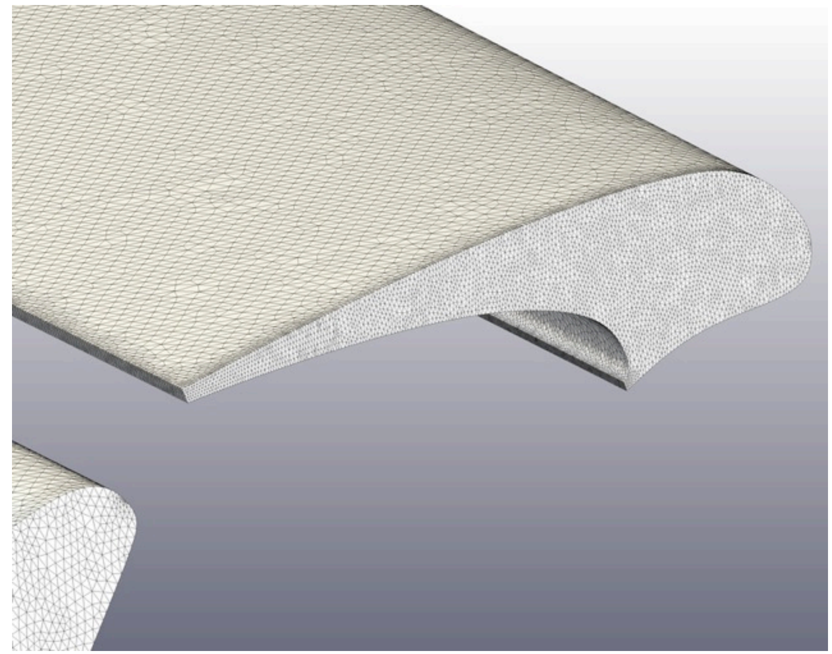

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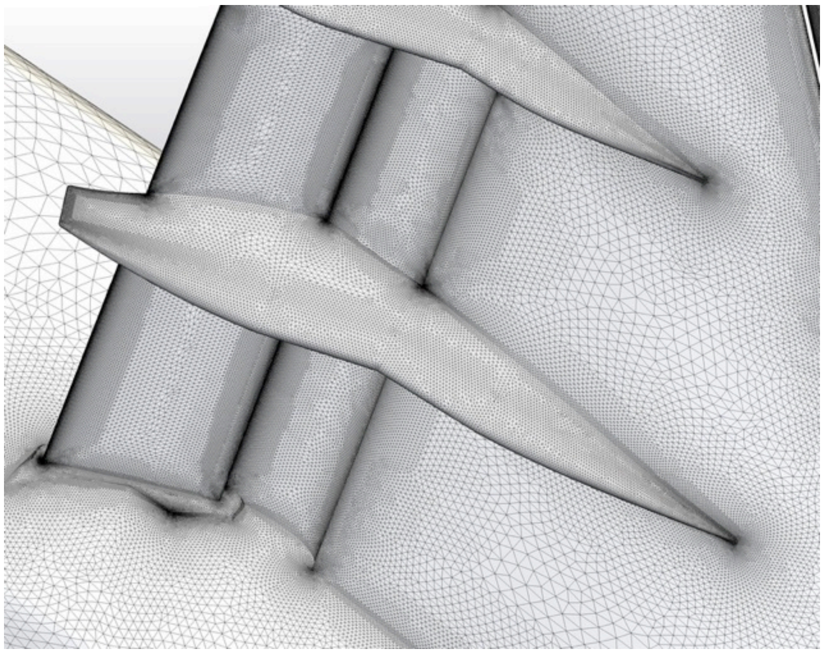
Case 2 Grid Description – Flap Inboard

VGRID



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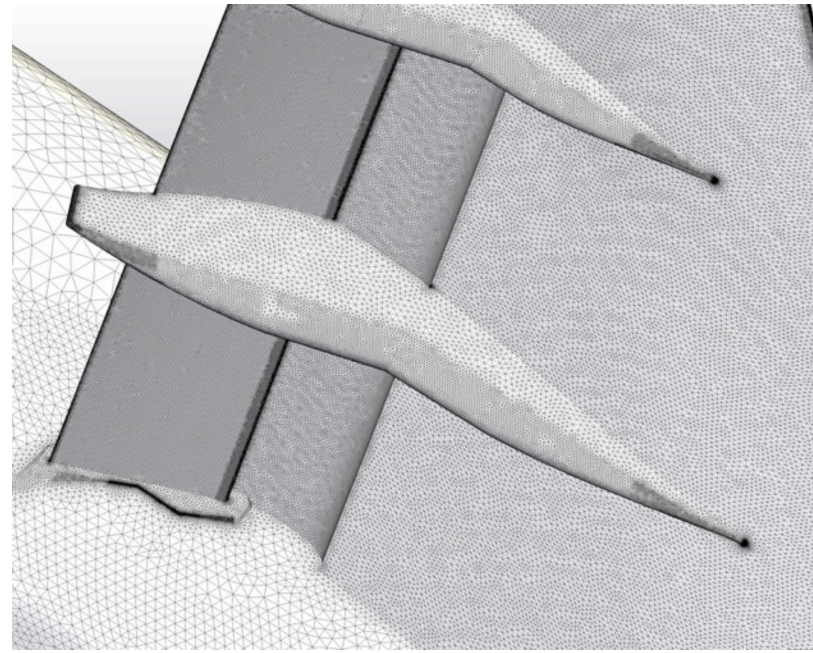

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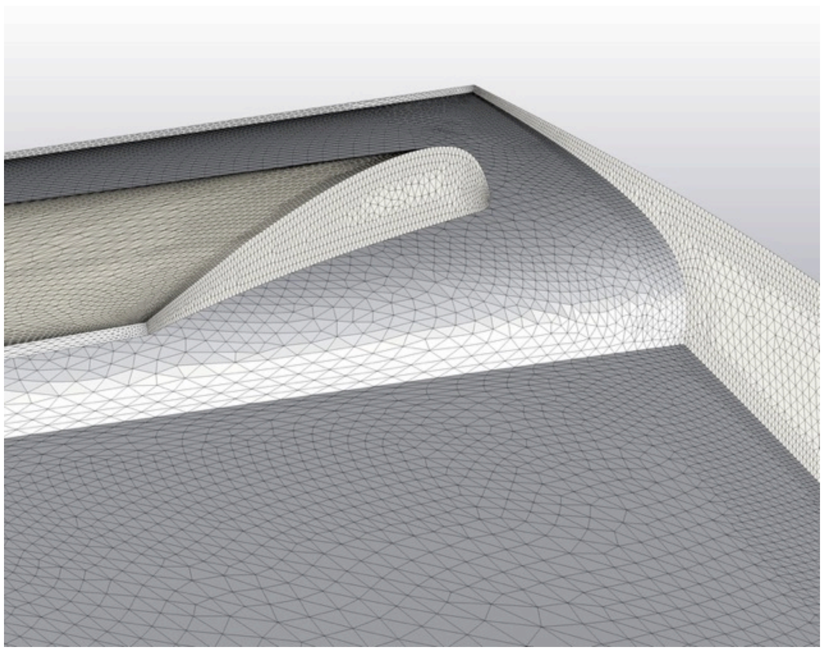

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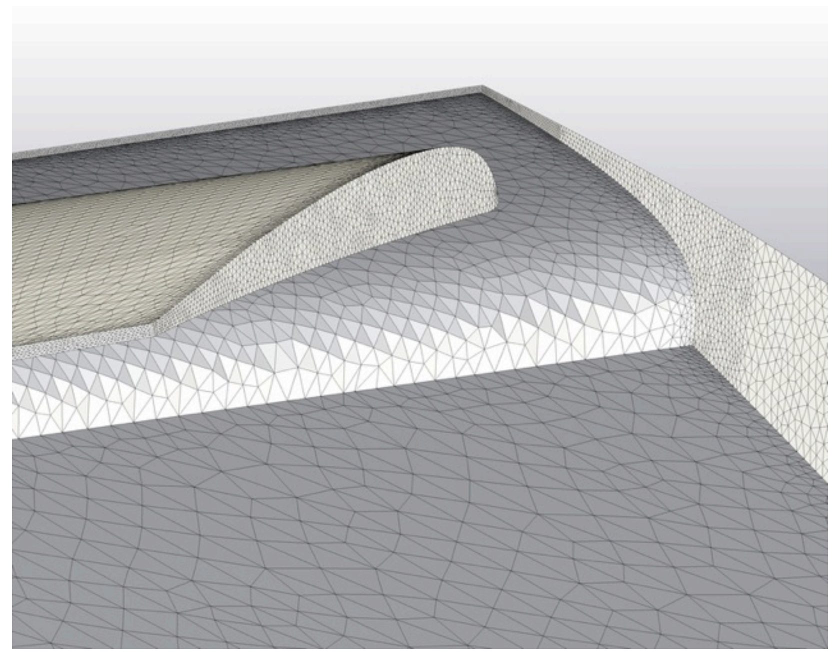

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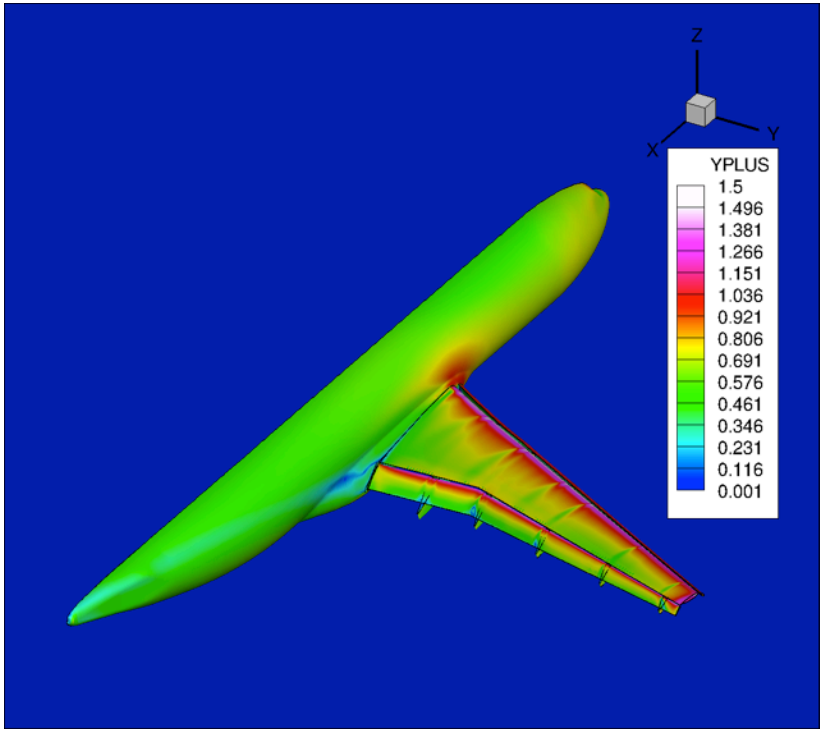
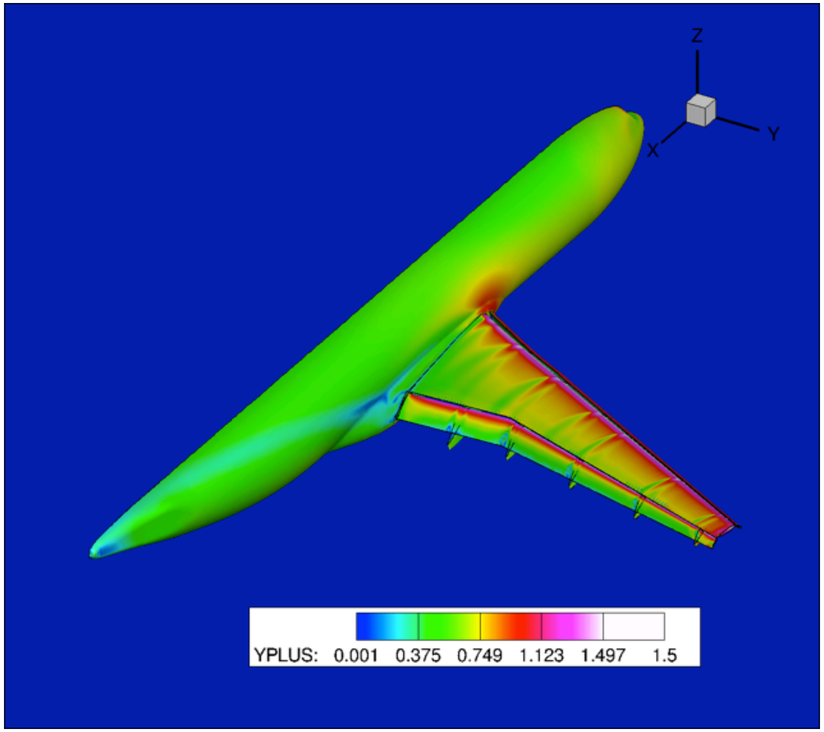
Y+ for VGRID Grids, Alpha 16°

k-ω



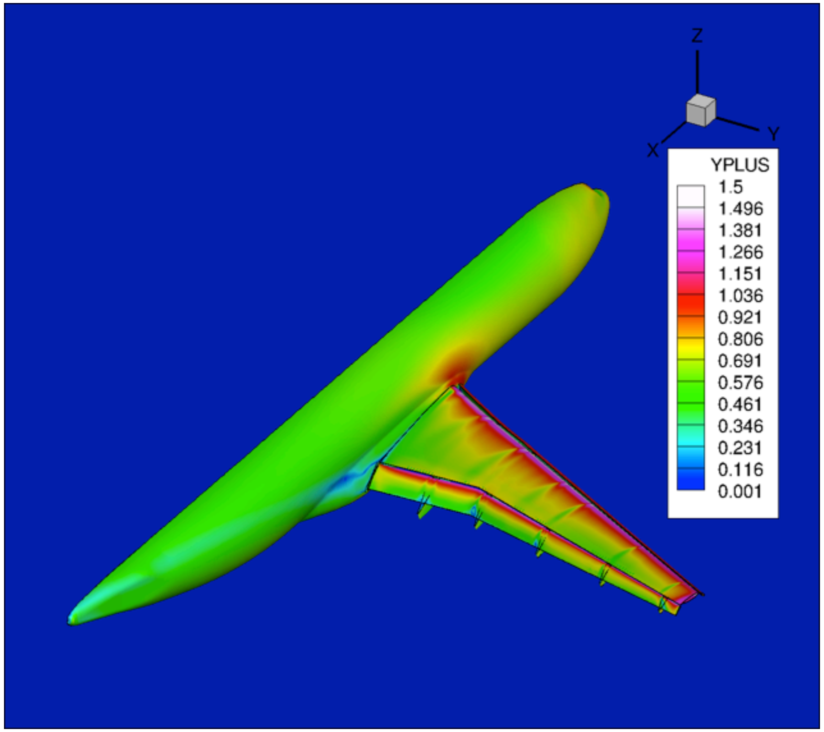
S-A



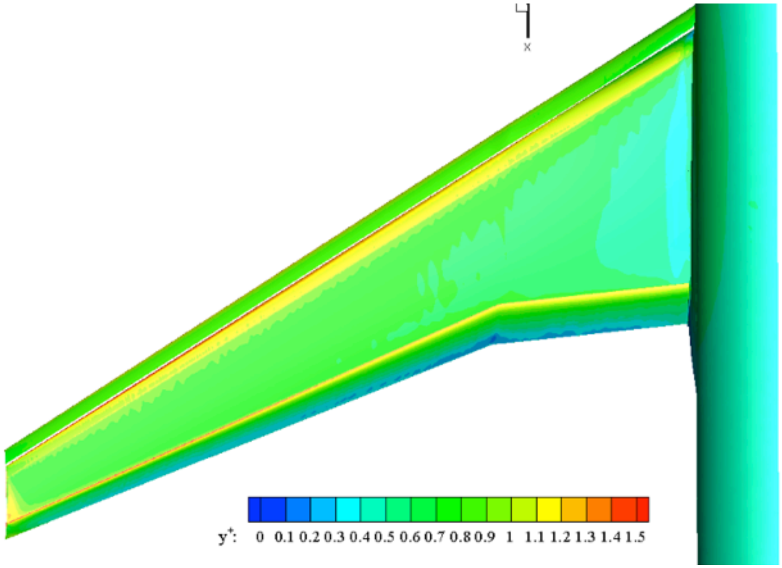
- y+ less than 1 over majority of aircraft

Y+ for k-ω
Alpha 16°

VGRID



ICEM



- y+ less than 1 over majority of aircraft

NSU3D

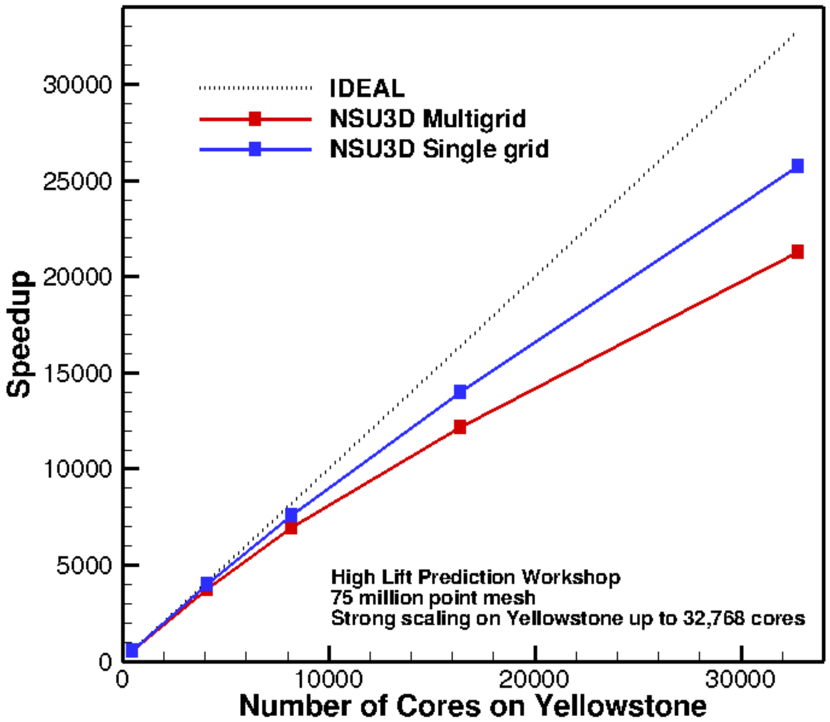
- Unstructured Reynolds Averaged Navier-Stokes solver
  - Vertex-based discretization
  - Mixed elements (prisms in boundary layer)
  - Edge data structure
  - Matrix artificial dissipation
    - Option for Roe upwind scheme with gradient reconstruction
  - No cross derivative viscous terms
    - $\nabla(\mu \nabla v)$: (Similar to incompressible Full NS)
    - Option for full Navier-Stokes terms
      - Extended stencil with edge-based normal derivatives
      - Similar to most other node-based unstructured solvers

NSU3D – Turbulence Models

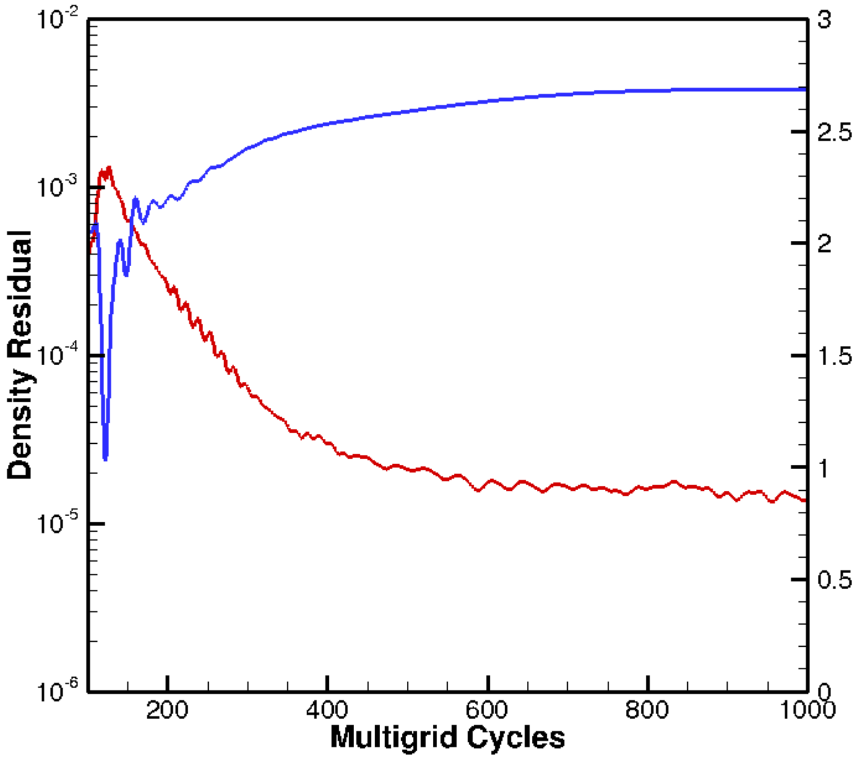
- Spalart-Allmaras
  - (original published form)
- Wilcox k-omega model
- Option for
  - Mentor SST Model
    - Not exercised

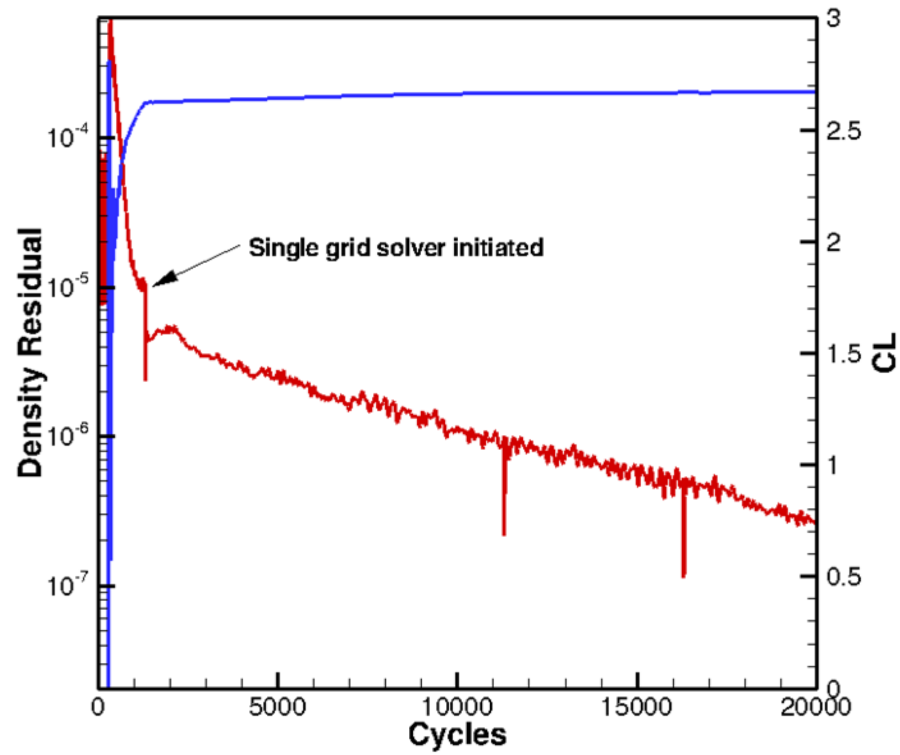
Solution Strategy

- Jacobi/Line Preconditioning
  - Line solves in boundary layer regions
    - Relieves aspect ratio stiffness
- Agglomeration Multigrid
  - Fast grid independent convergence rates
- Linear solver option
  - Multigrid or single grid
  - Line Jacobi subiterations
  - GMRES Krylov method for complete convergence
- Good scalability demonstrated on up to 32,768 cores



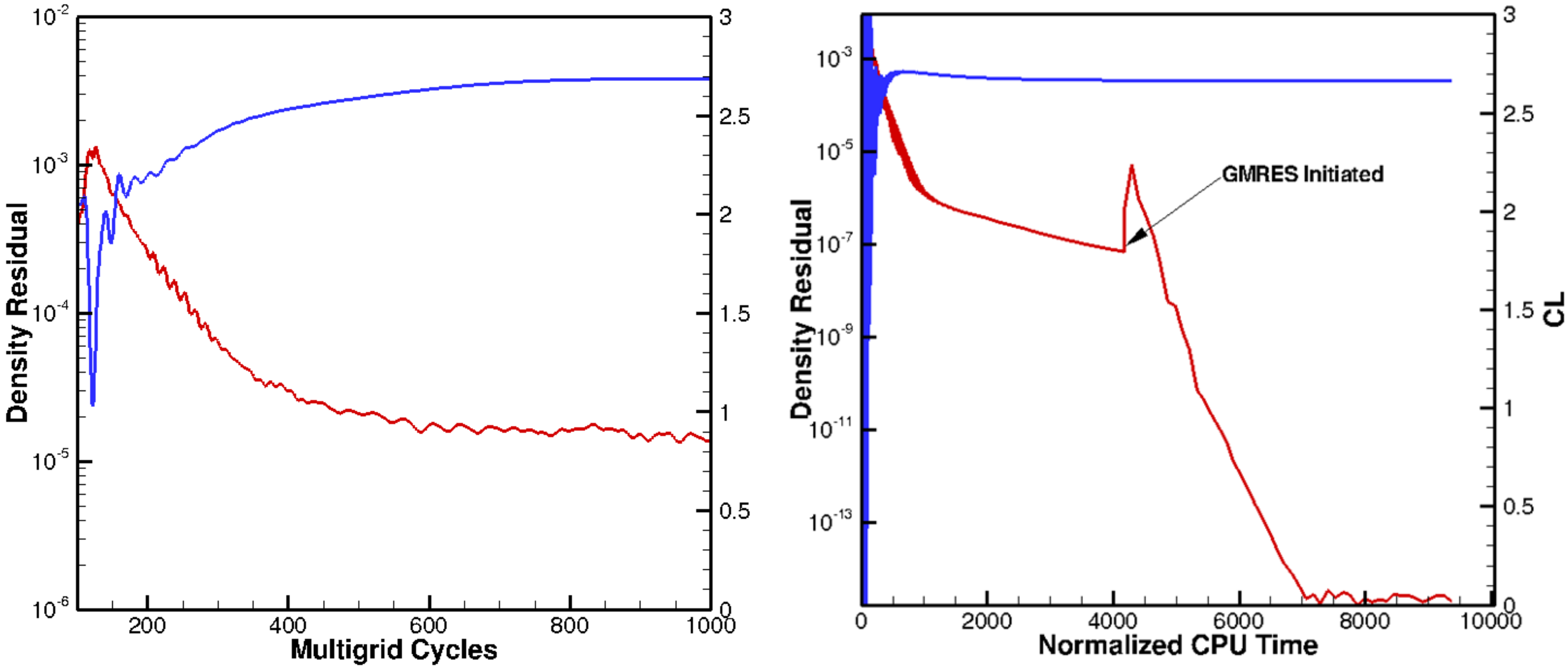
NSU3D Multigrid Convergence





- Cases run 1000 multigrid cycles
  - Engineering accuracy for forces in most cases (ICEM/Bombardier)
  - Residual convergence stalls
- Further convergence using up to 20,000 single grid cycles
  - UWYO runs (VGRID meshes)

NSU3D Multigrid Convergence



- Convergence to machine precision possible using Newton-Krylov method
  - Linear multigrid preconditioned GMRES
    - 50 Krylov vectors, 10 restarts per non-linear update
- Restarted from linear multigrid solution
- Demonstration only on selected cases

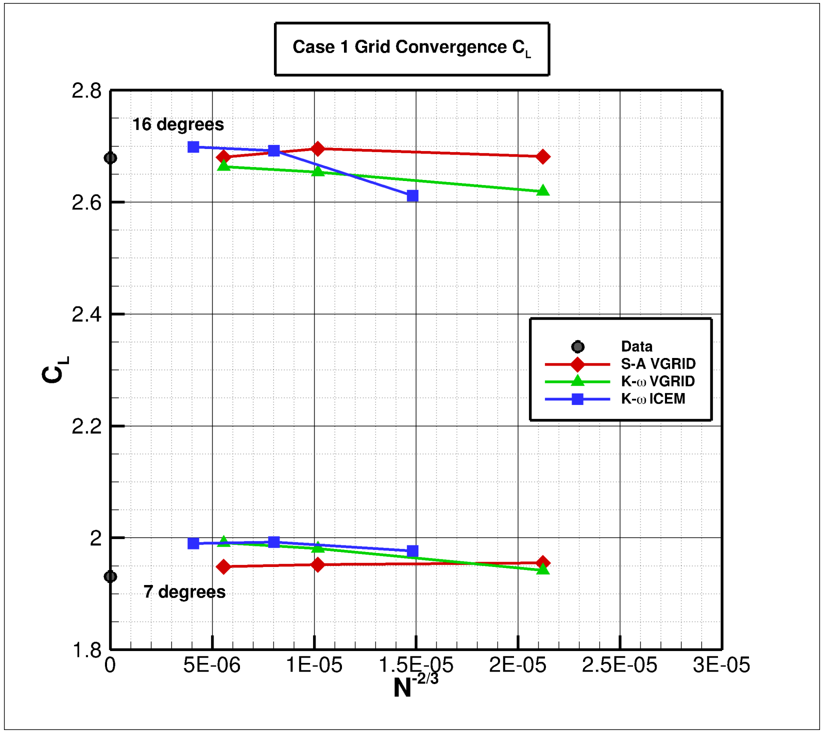
Results Presentation

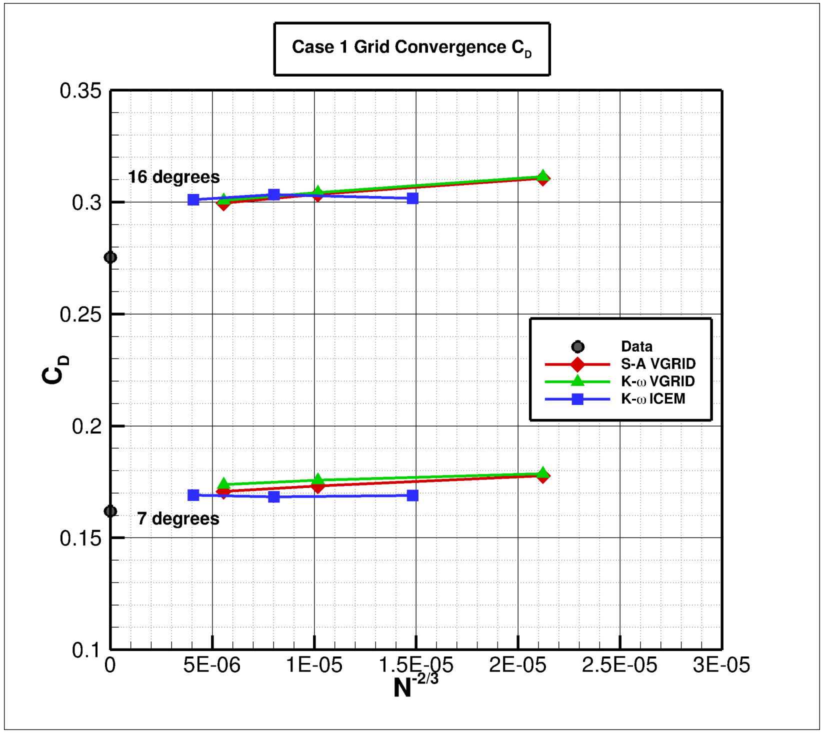
- Case 1
  - Grid Convergence of a simplified geometry, ie without fairings
  - Compared to experimental data to show if solutions are converging toward data
  - Due to simplified geometry, C_{LMAX} is not predicted well, therefore only two incidences (7^o, 16^o) computed
- Case 2
  - Compared to experimental data using medium grid, with 2 grid types and 2 turbulence models*

Case 1

- Mach Number = 0.175
- Reynolds Number = **15.1** million based on MAC
- Angle of Attack = 7° and 16°
- Grids
  - VGRID
    - S-A and k-ω
  - ICEM-TETRA
    - k-ω
    - No Velocity Profile Plots

Case 1 Results

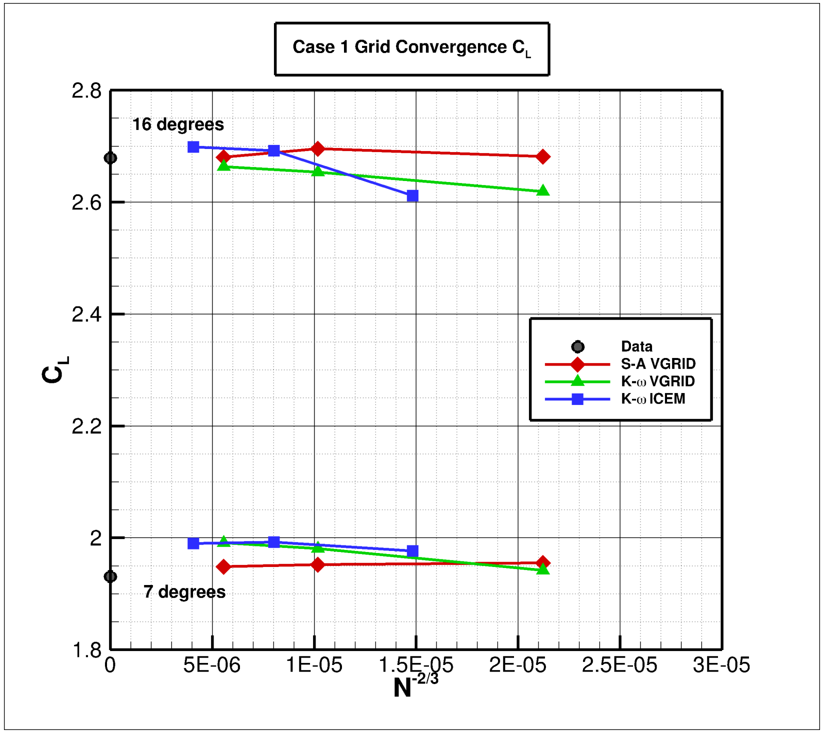


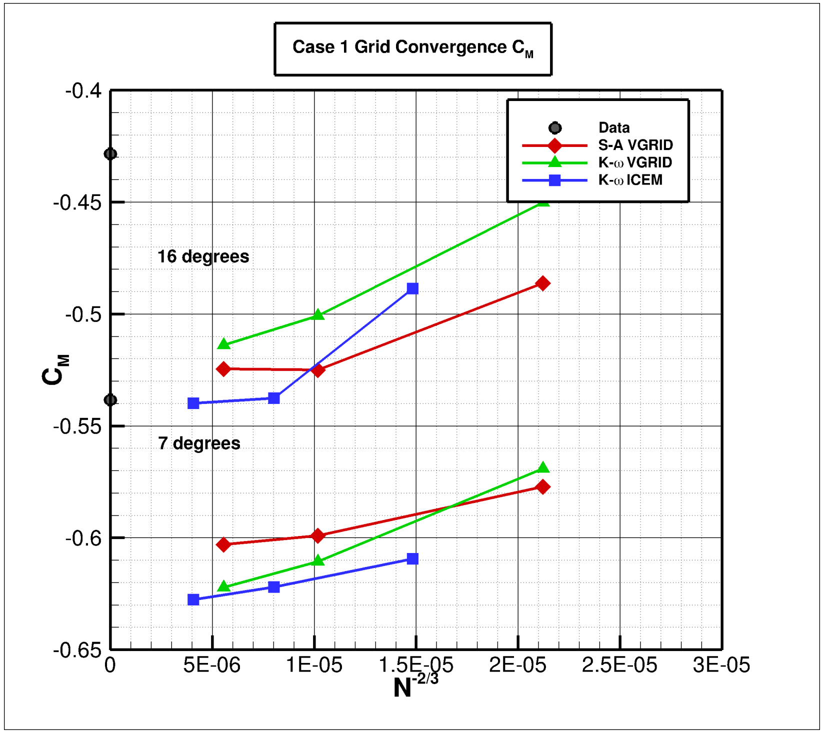


- Linear convergence of CL at lower angle of attack for both grids, indicative of second order accuracy
- VGRID more linear than ICEM at higher angle of attack

- Linear convergence of CD across both grids and at both incidences, indicative of second order accuracy

Case 1 Results





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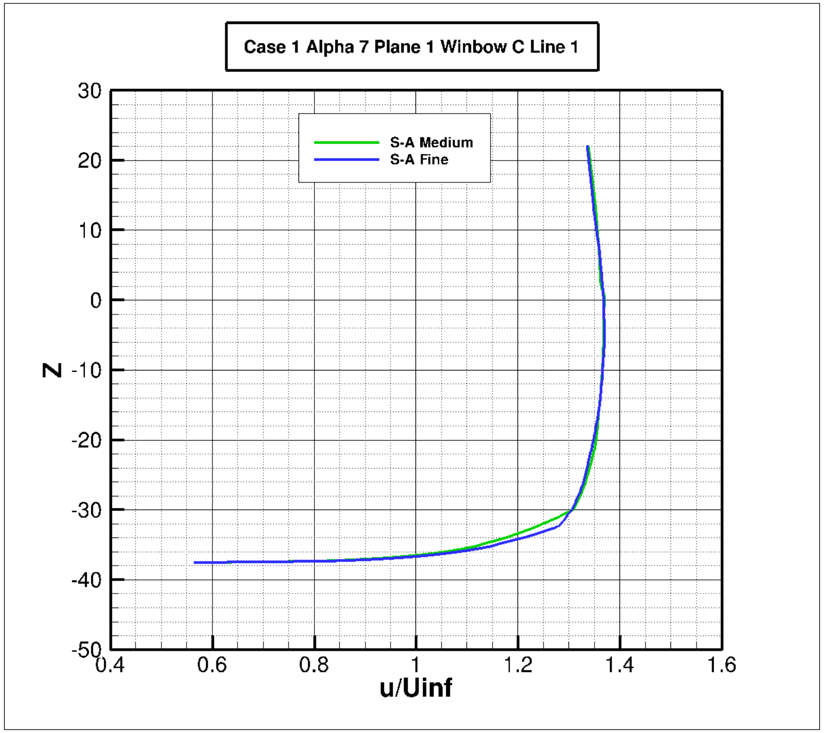
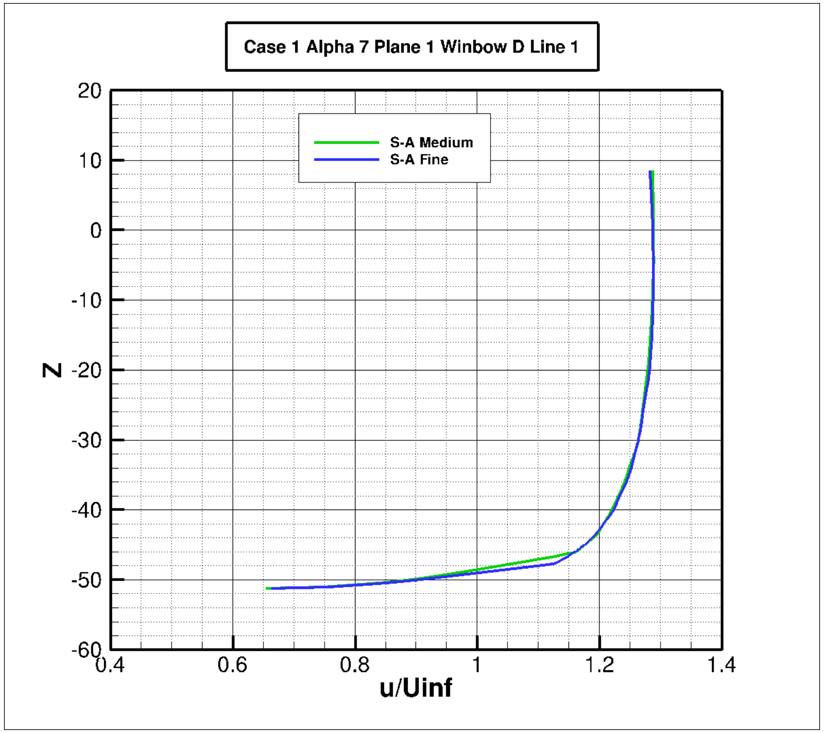
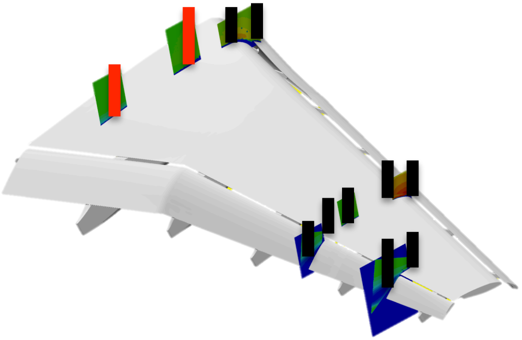
- CM convergence linear at 7° incidence
- Irregular convergence at 16° incidence
  - VGRID k-ω most linear

Case 1 Velocity Profile Results
Alpha 7°, S-A Model





- Good agreement between medium and fine grid velocity profiles



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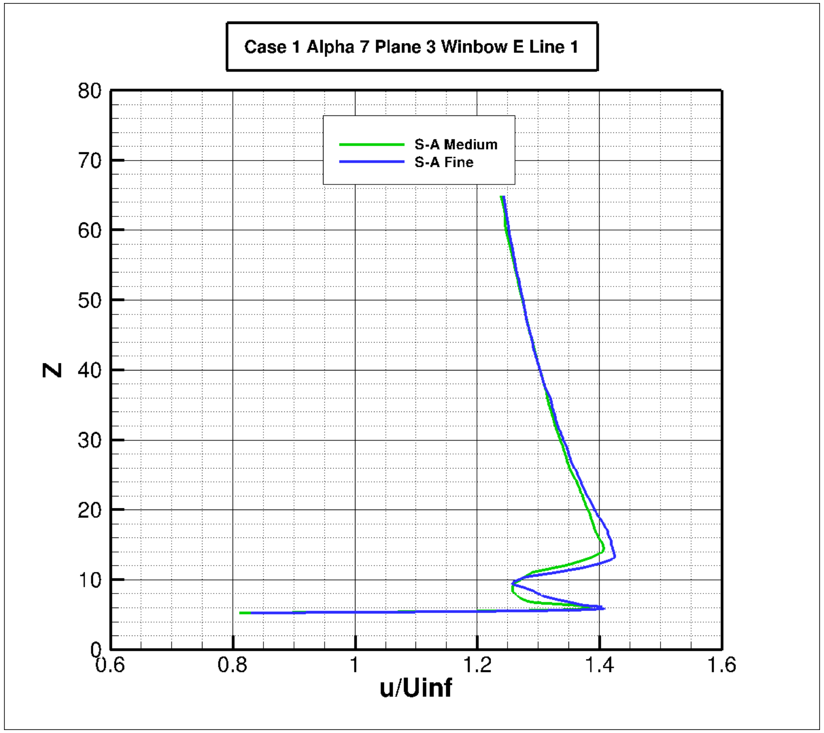

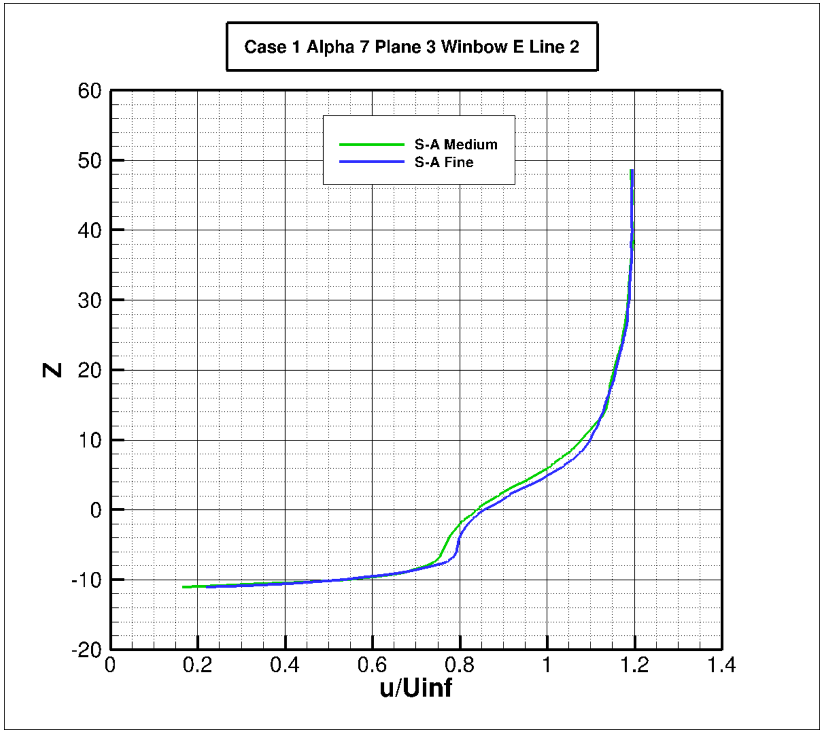

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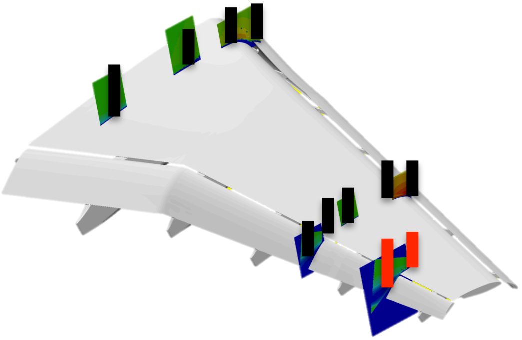
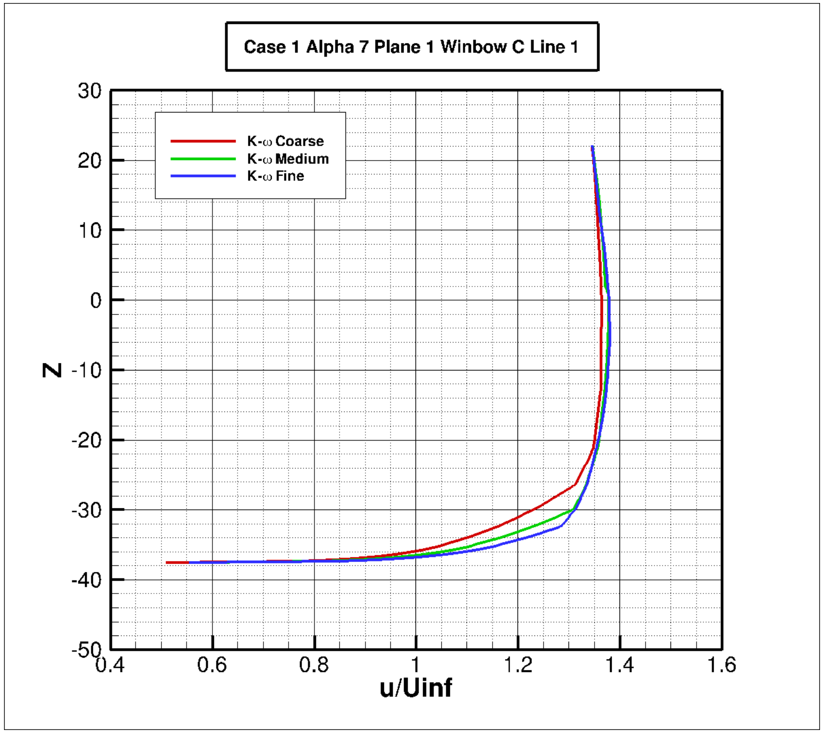
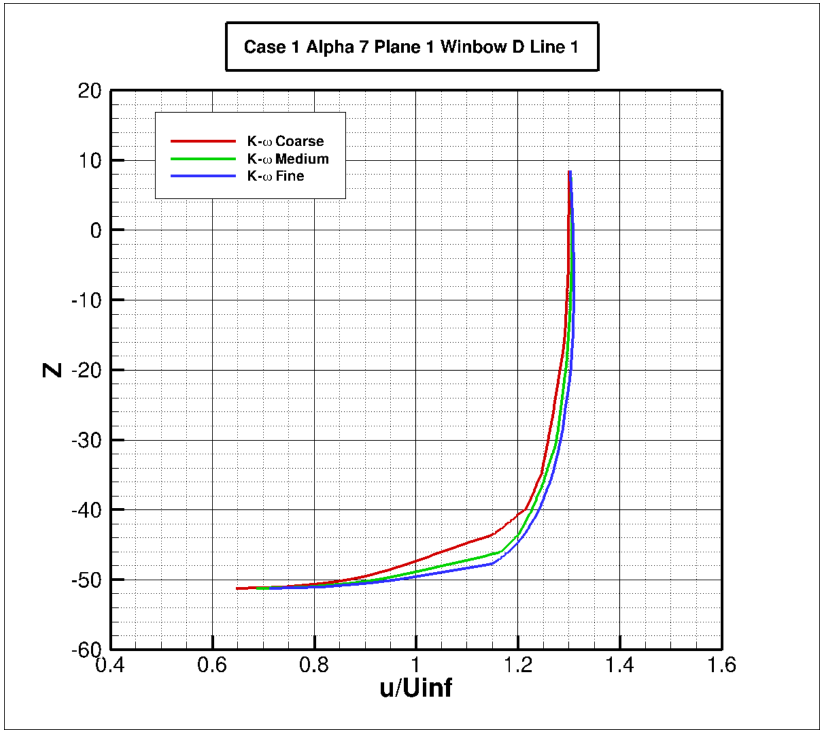
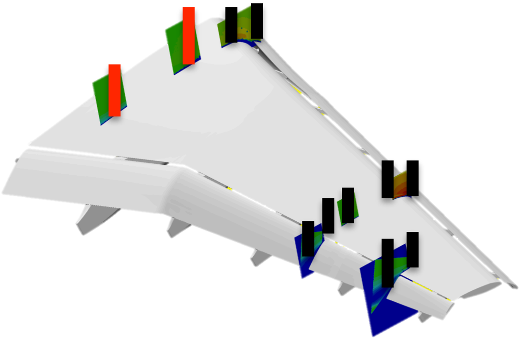


Case 1 Velocity Profile Results
Alpha 7°, k-ω Model





- Apparent grid convergence of velocity profiles with decreasing differences with grid resolution



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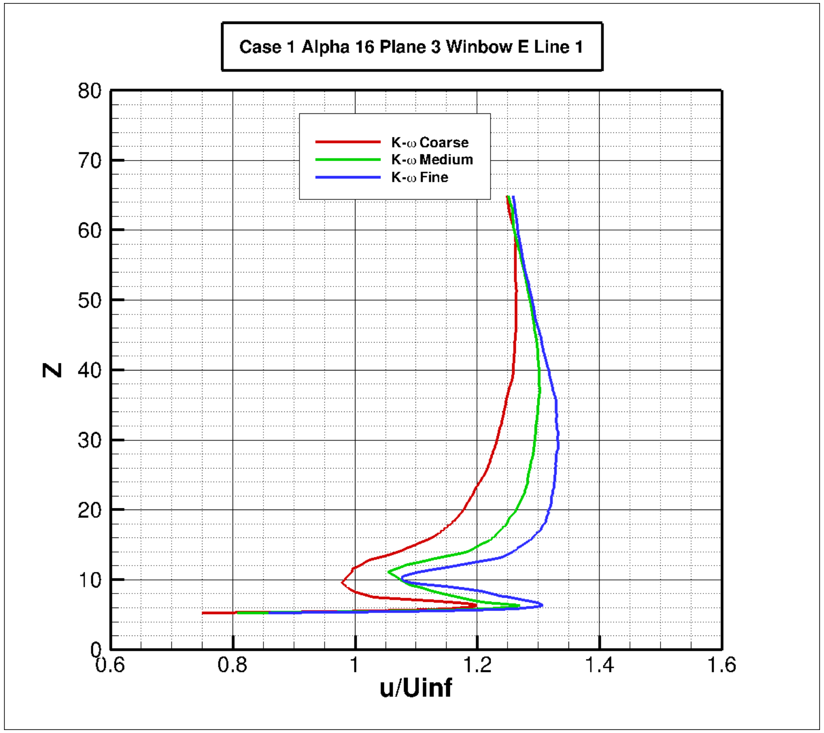

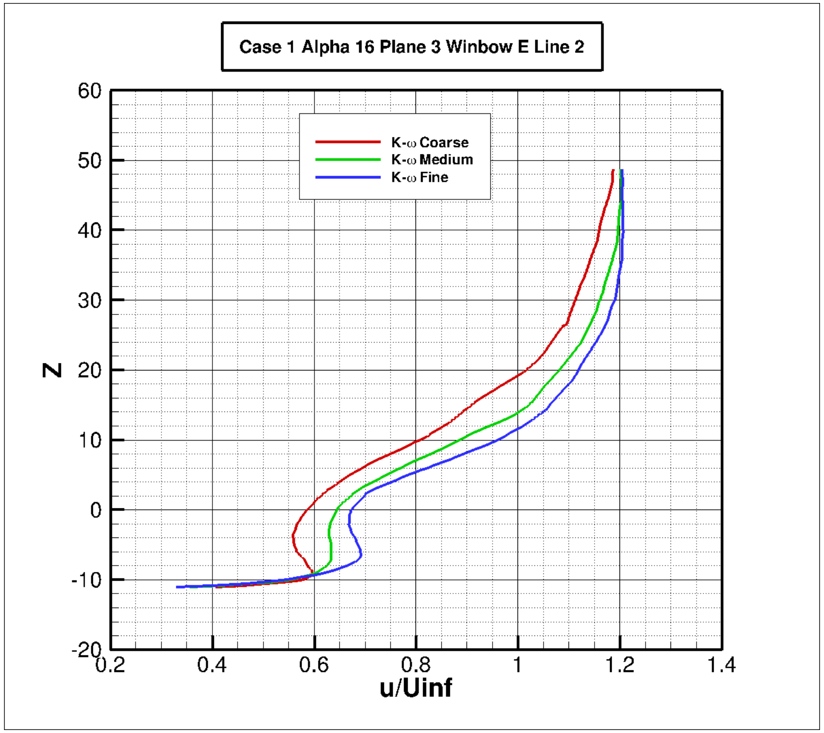

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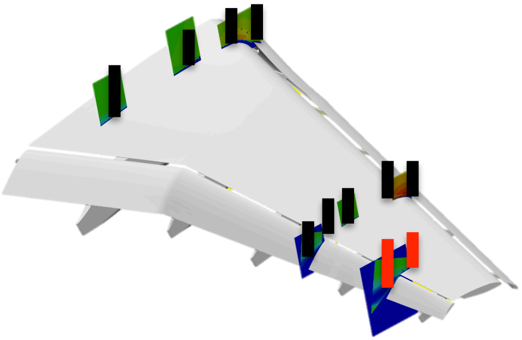
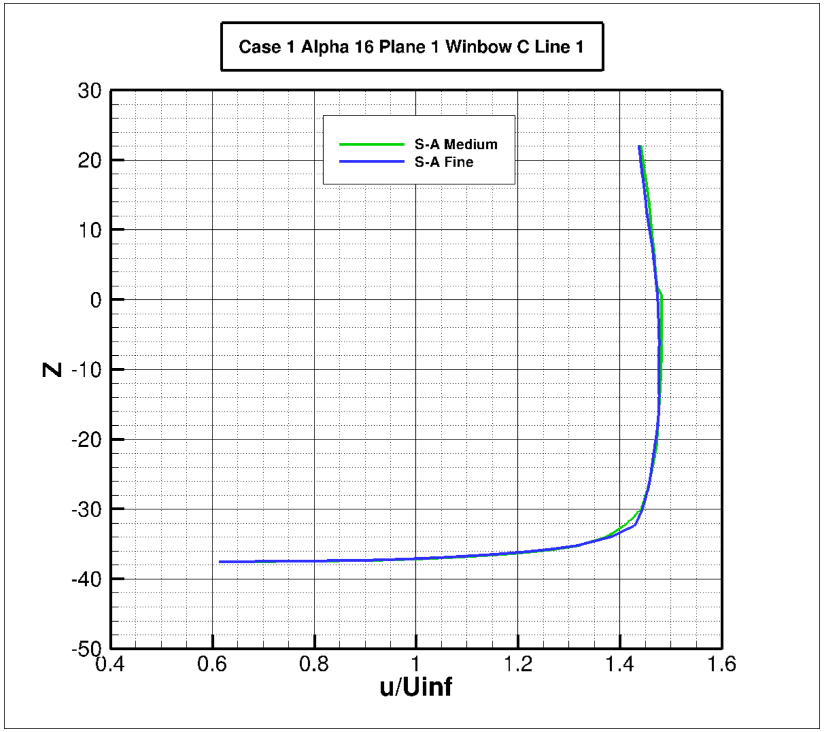
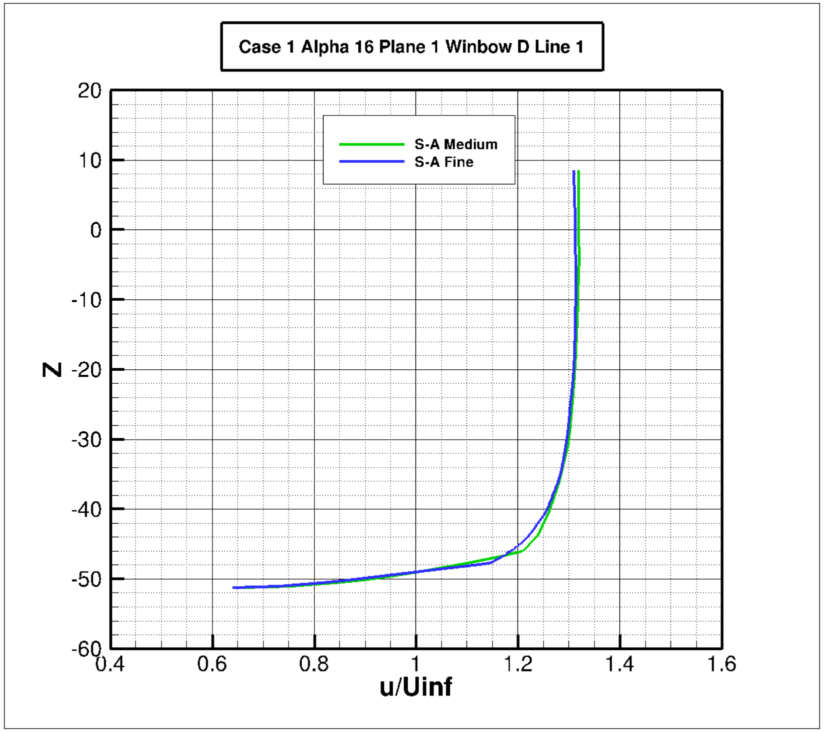


- Larger differences in outboard and downstream data

Case 1 Velocity Profile Results
Alpha 16°, S-A Model





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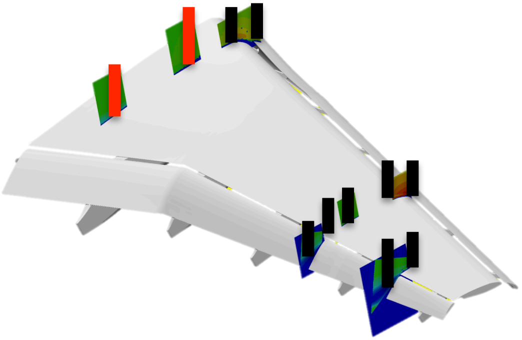

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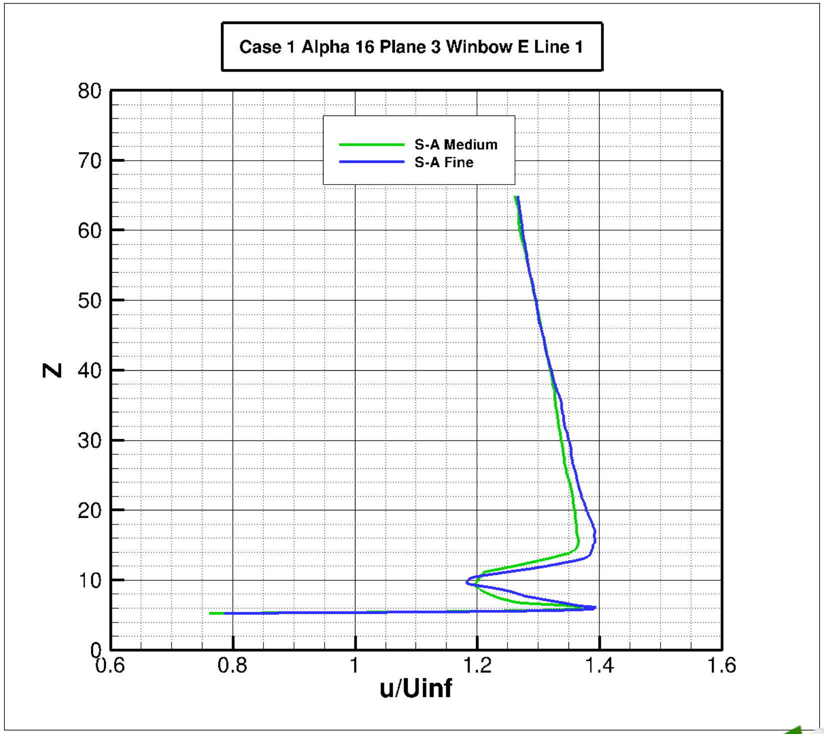

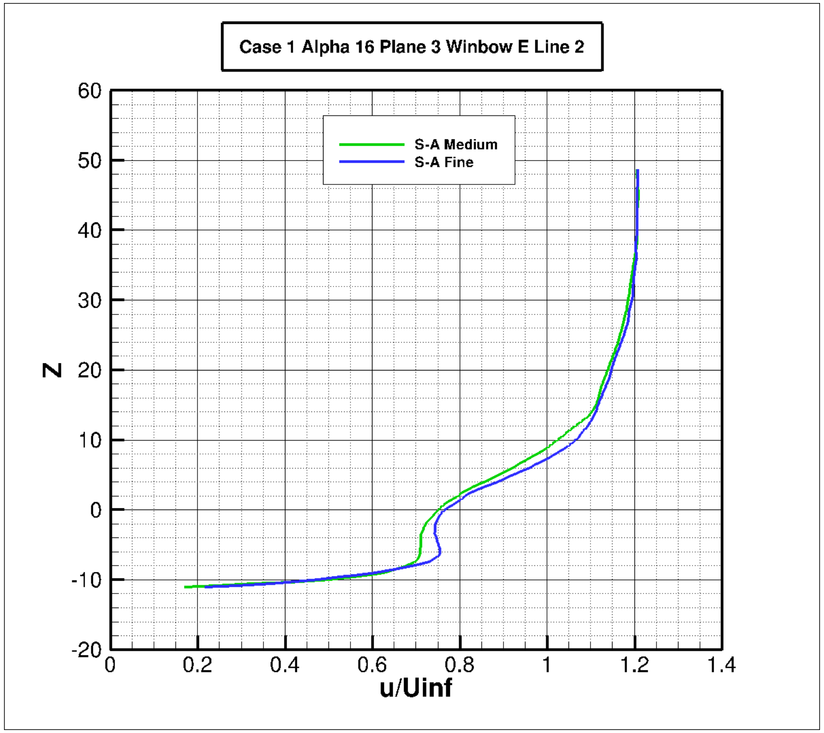

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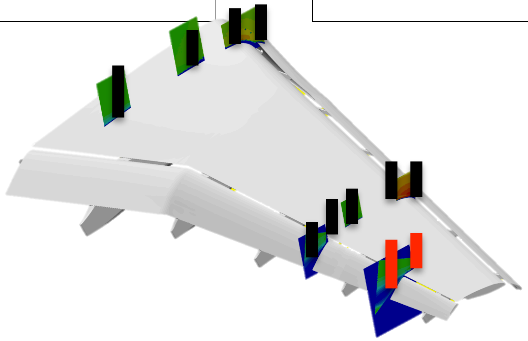
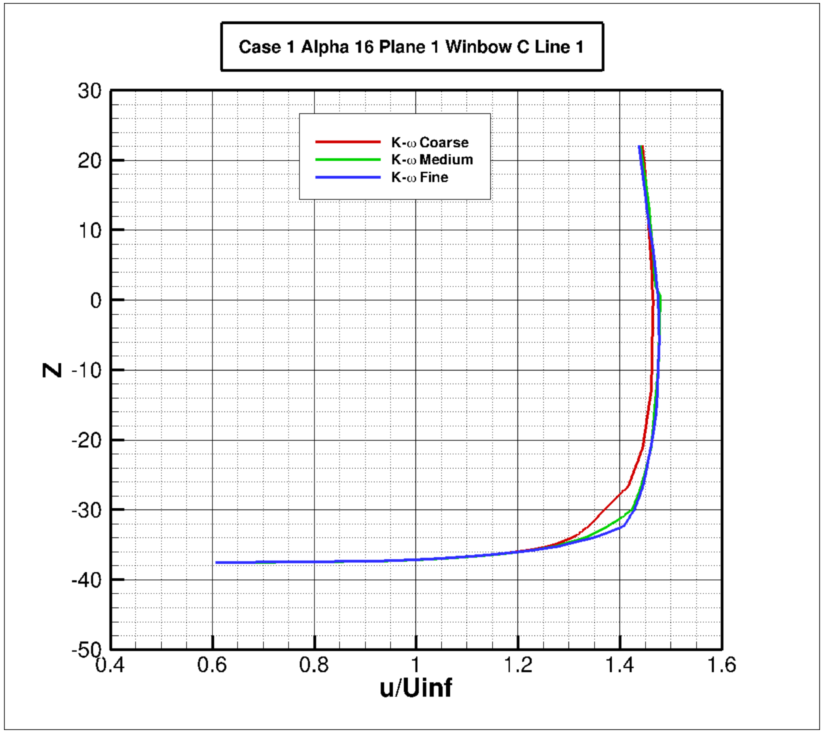
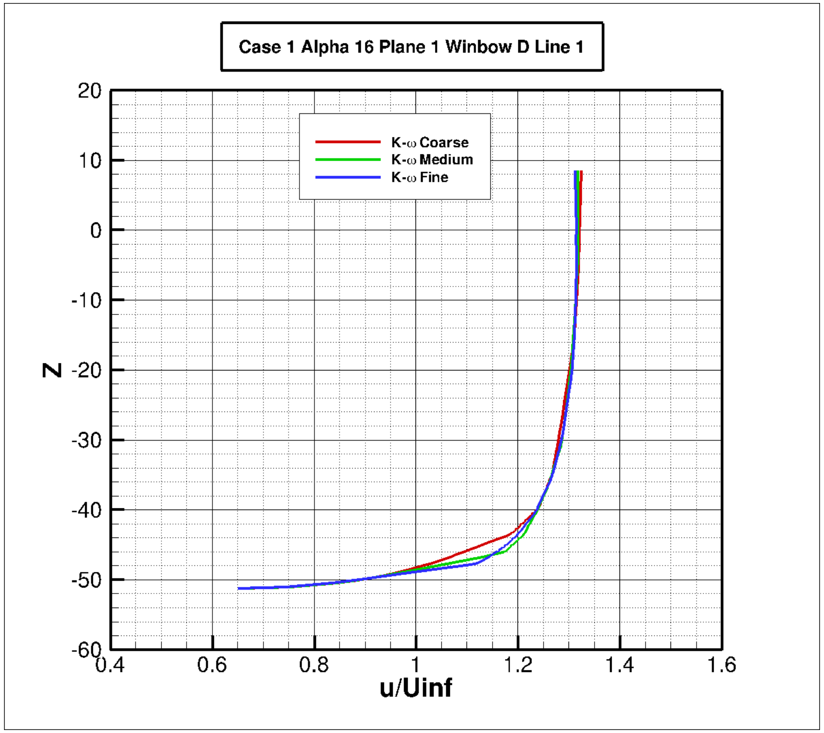
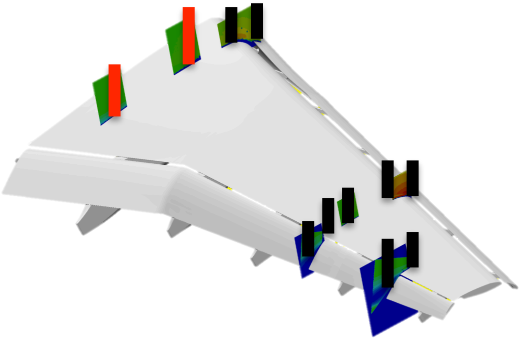


Case 1 Velocity Profile Results Alpha 16°, k-ω Model

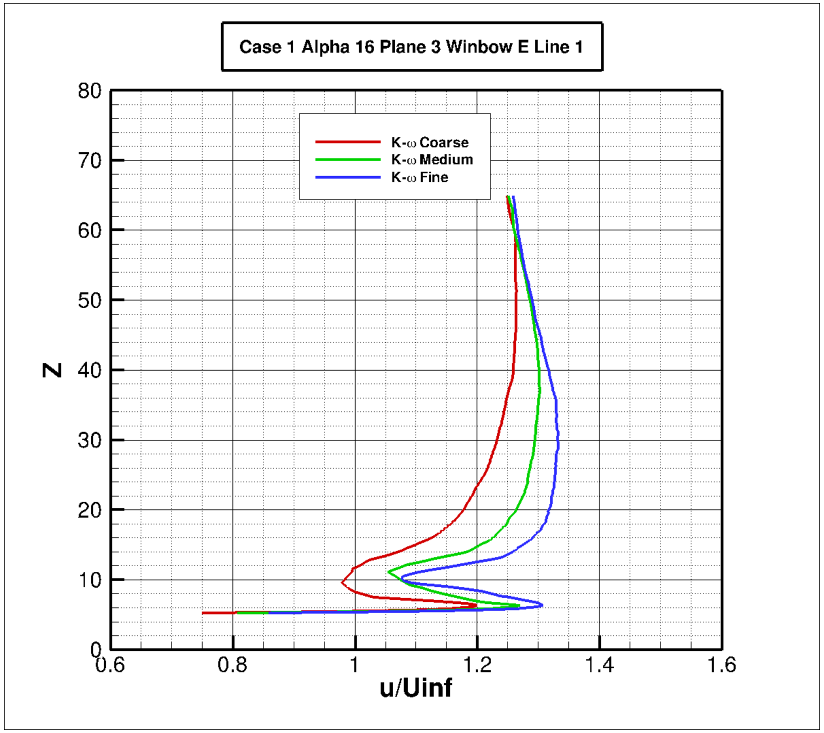


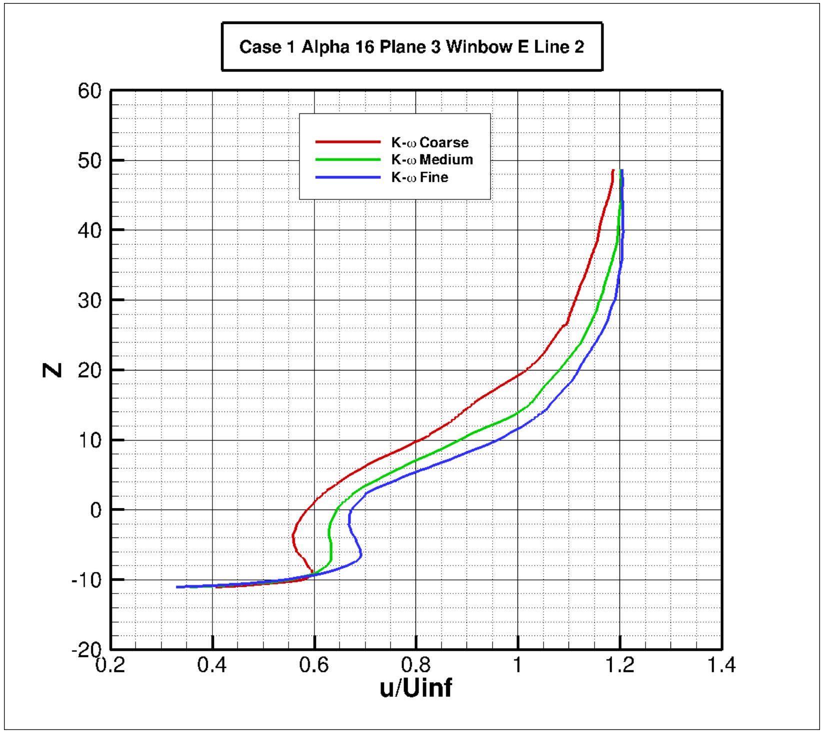


- Apparent grid convergence of velocity profiles with decreasing differences with grid resolution

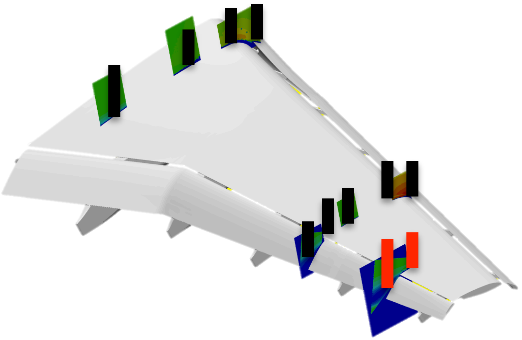


Case 1 Velocity Profile Results Alpha 16°, k-ω Model





- Apparent grid convergence of velocity profiles with decreasing differences with grid resolution

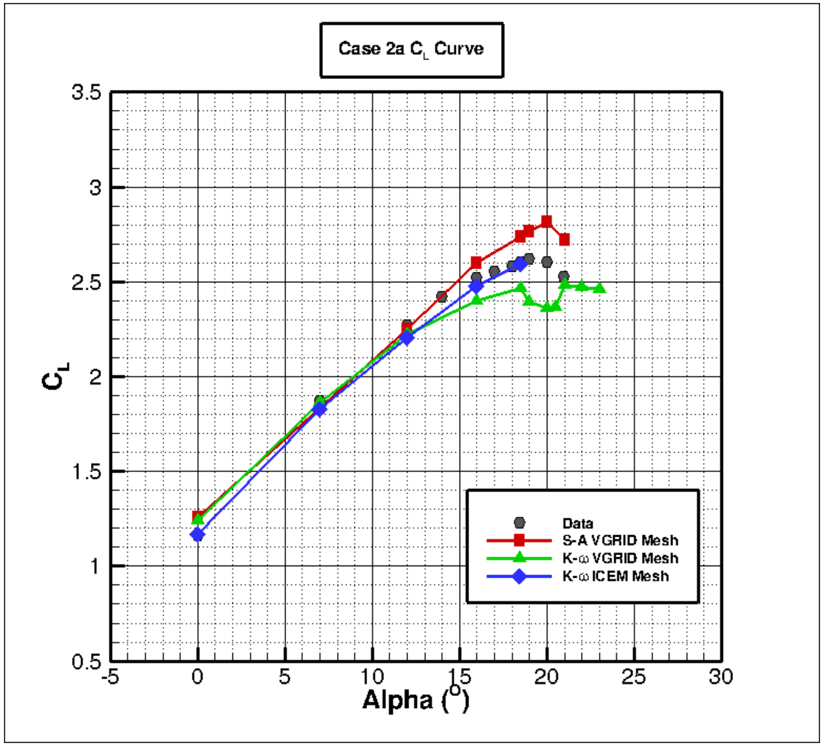


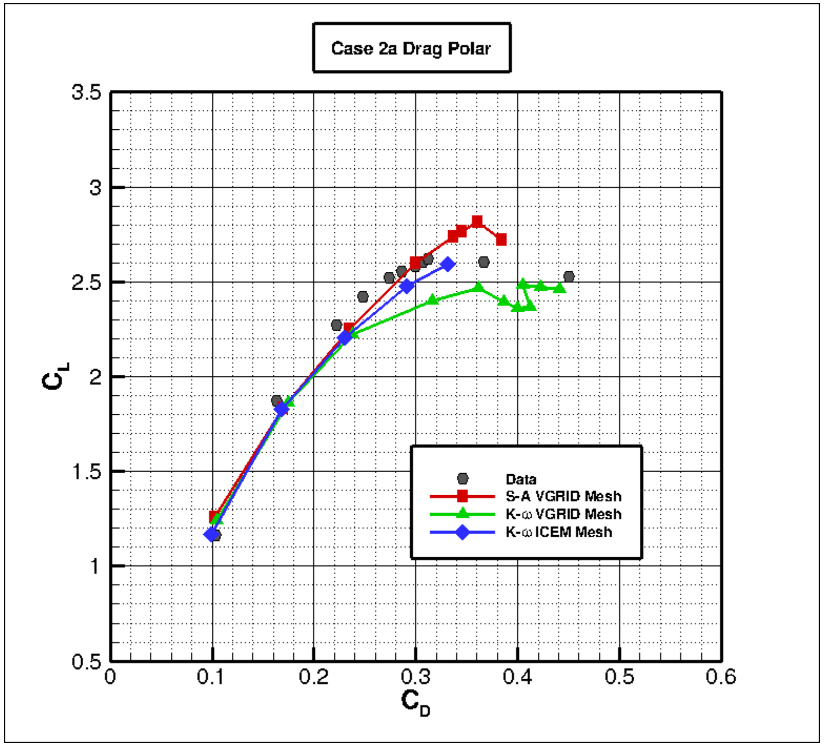
- Larger differences in outboard and downstream data

Case 2a

- Mach Number = 0.175
- Reynolds Number = **1.35** million based on MAC
- Angle of Attack = 0°, 7°, 12°, 16°, 18.5°, 19°, 20°, 20.5°, 21°, 22°, and 23°
- Grids
  - VGRID
    - S-A and k-ω
  - ICEM-TETRA
    - k-ω

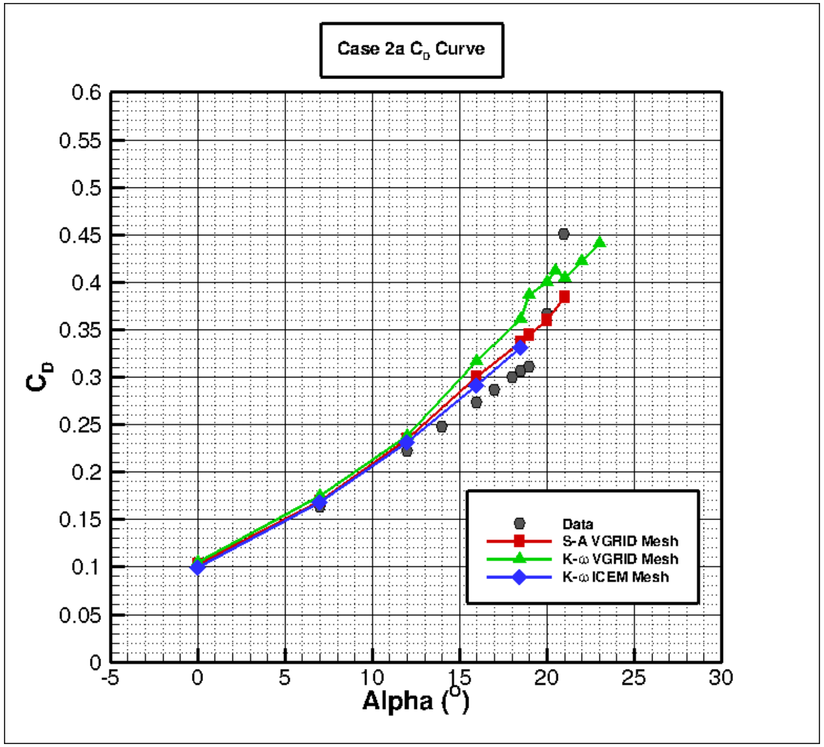
Case 2a Polars Results

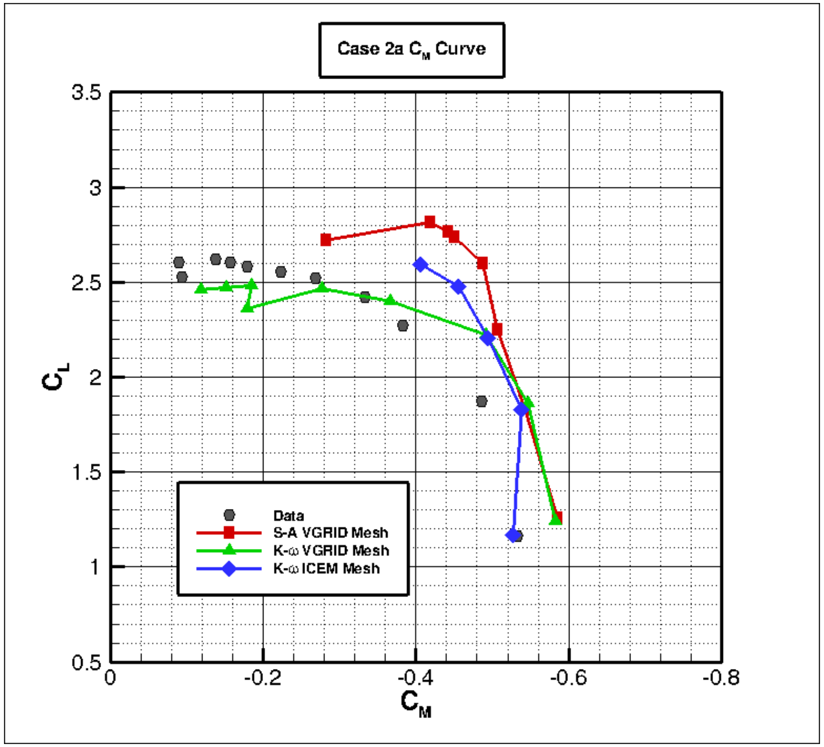




- S-A with the VGRID grid over predicts C_{LMAX}
- k-ω with the ICEM grid predicts C_{LMAX} well
- k-ω with the VGRID grid under predicts C_{LMAX}
- k-ω with the VGRID grid shows a flow reattachment post-stall

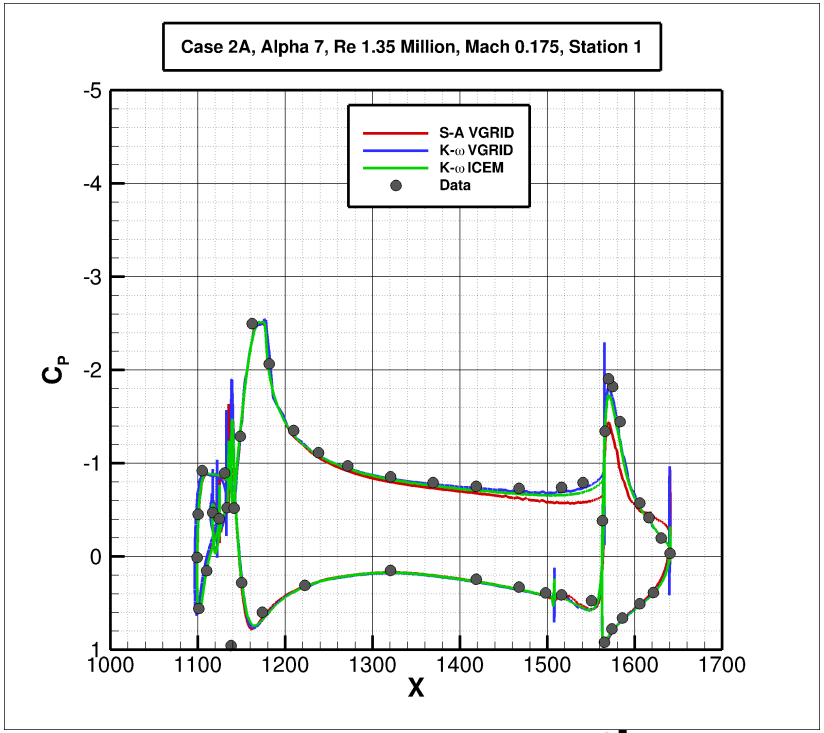
Case 2a Polars Results

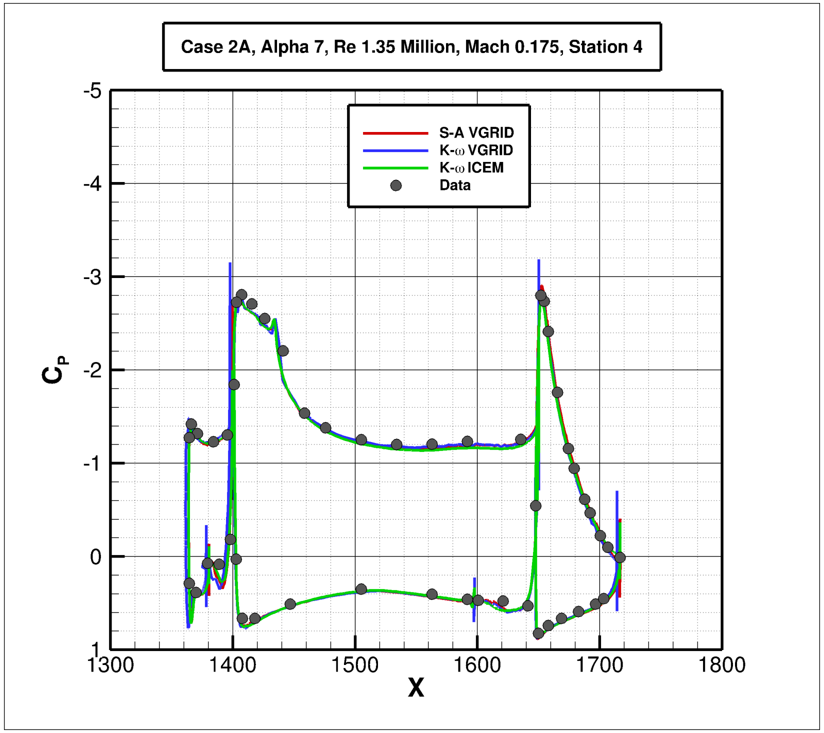


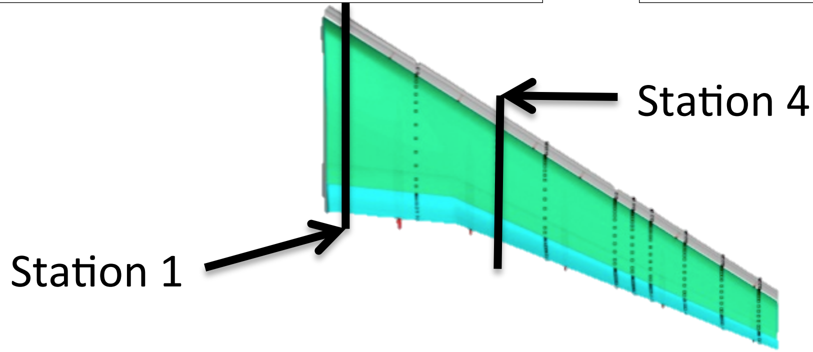


- k-ω on the VGRID grid shows best C_M agreement with experiment
- Other results show greater difference near stall

Case 2a C_P Results
Alpha 7°

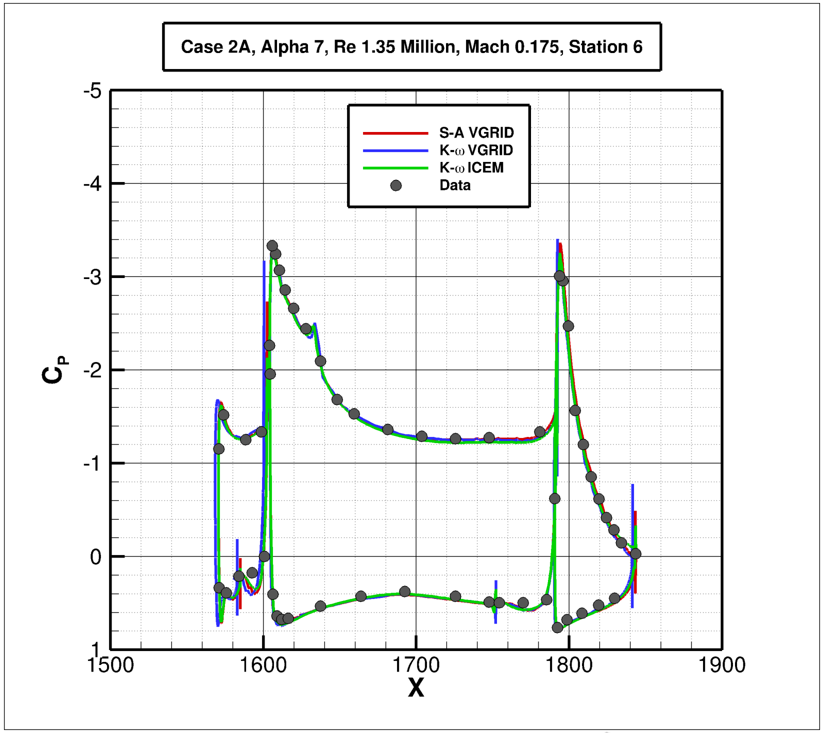


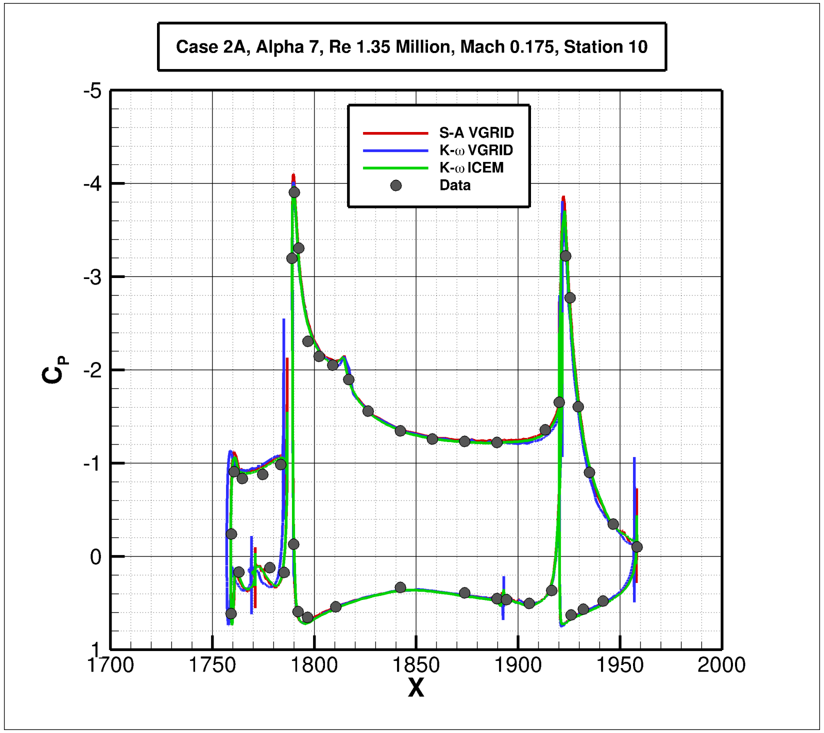


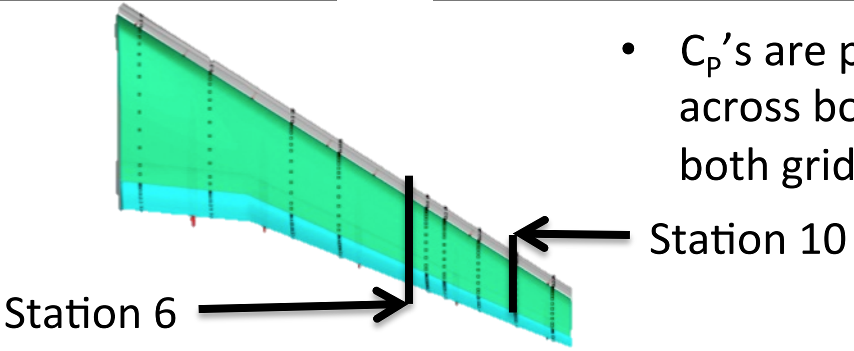


- C_P's are predicted well across both models and both grids

Case 2a C_P Results Alpha 7°

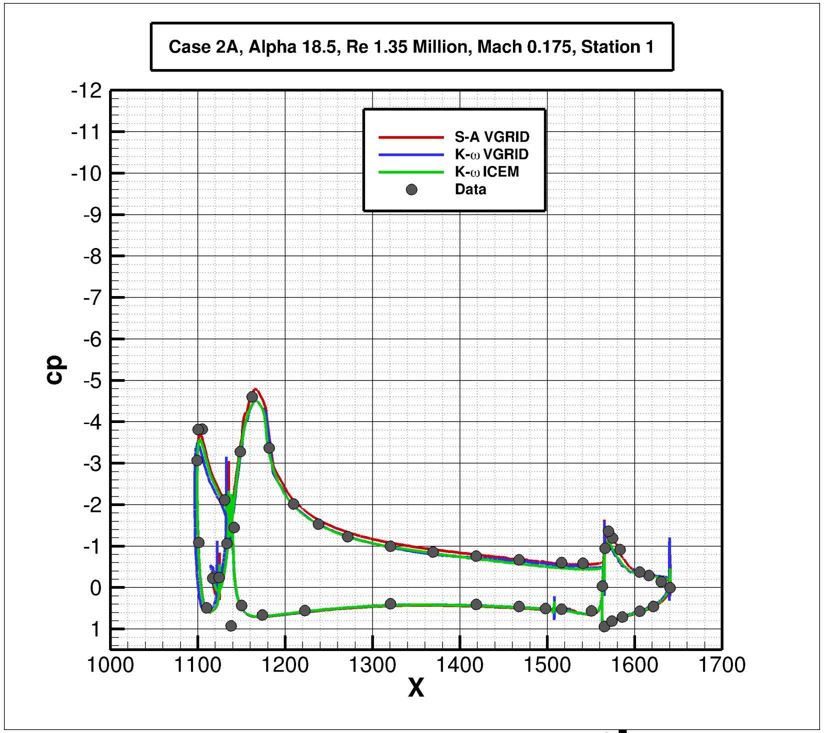


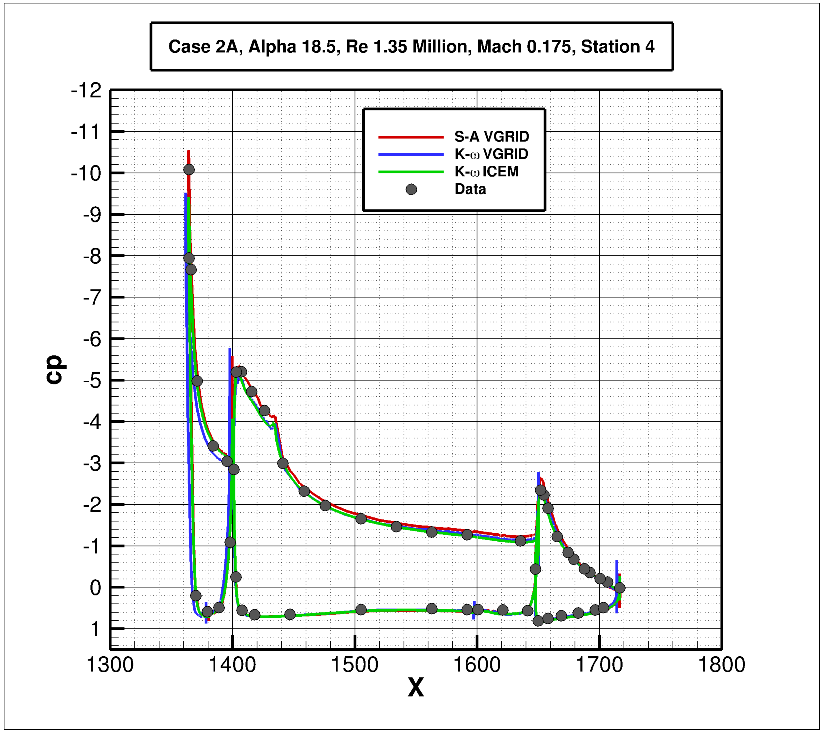


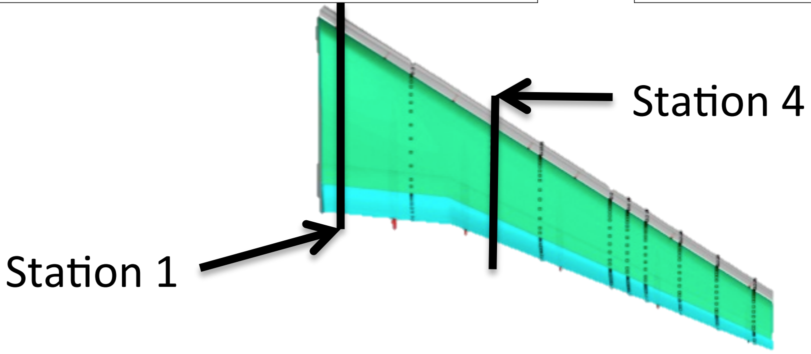


- C_P's are predicted well across both models and both grids

Case 2a C_P Results, Alpha 18.5°

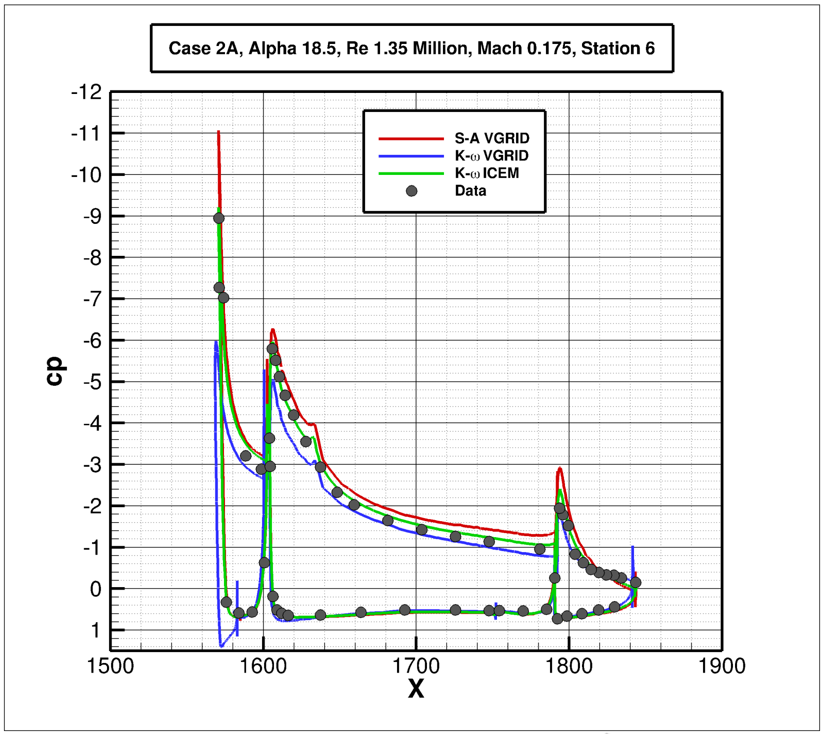


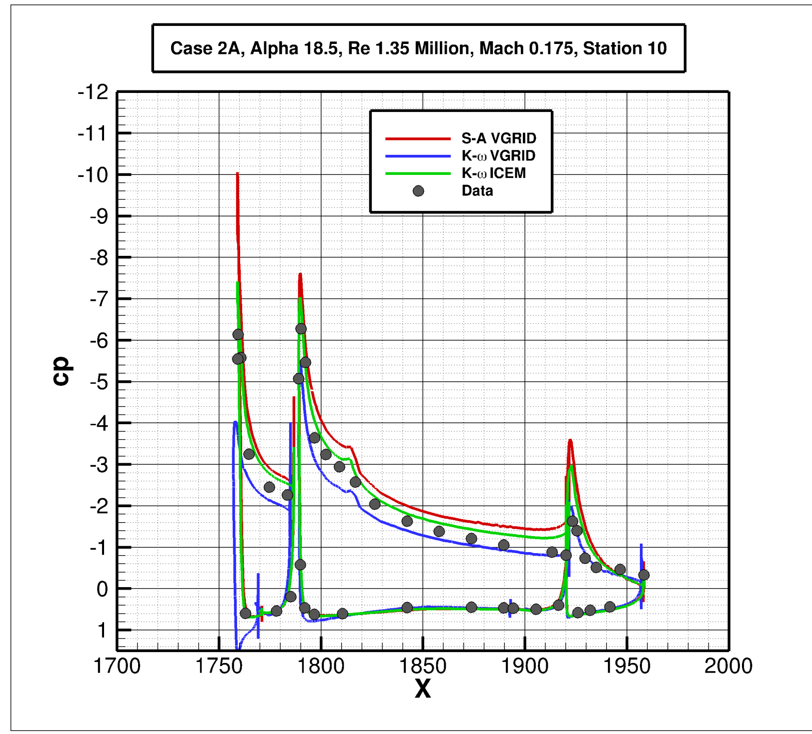




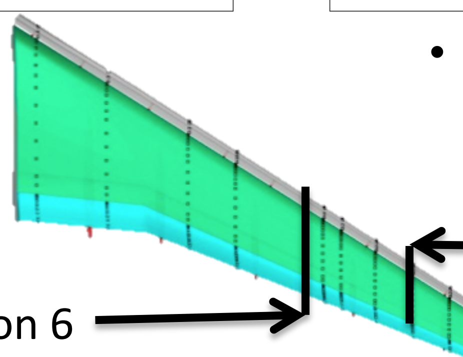
- C_P's are predicted well across both models and both grids

Case 2a C_P Results, Alpha 18.5°





- Agreement with experimental data degrades at outboard stations for higher angle of attack

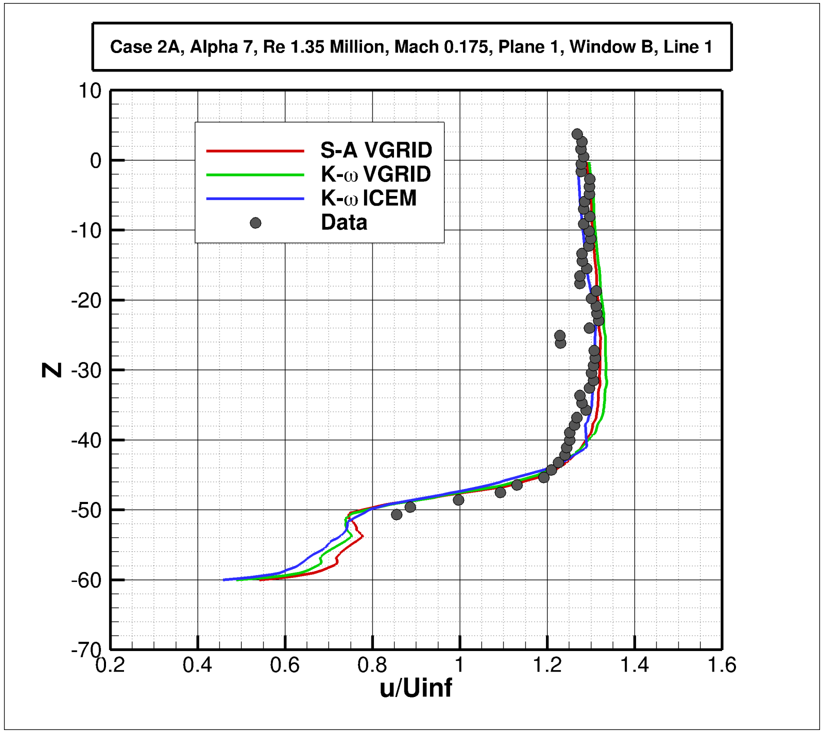


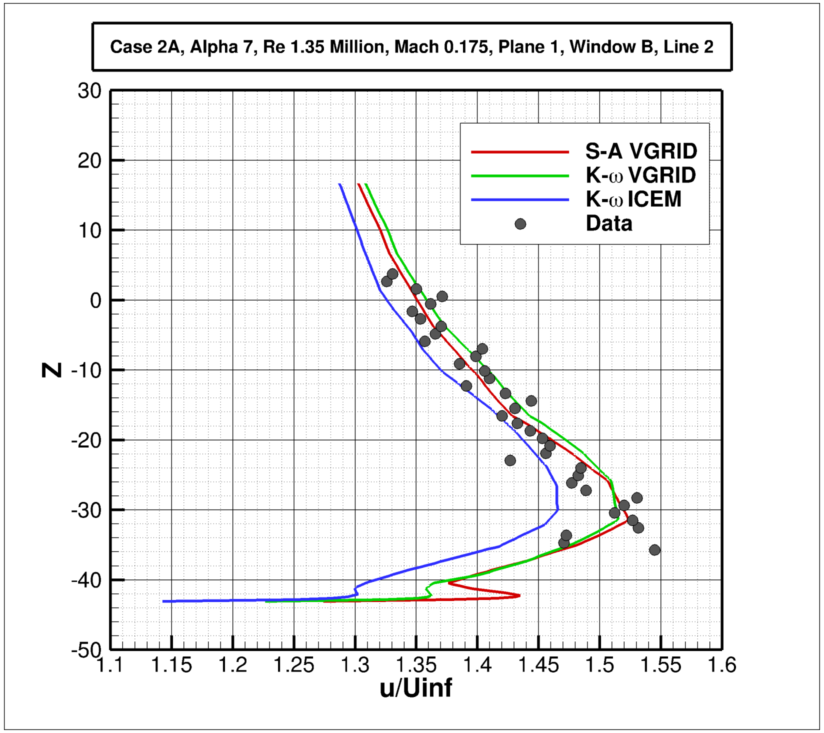
Station 10

Station 6

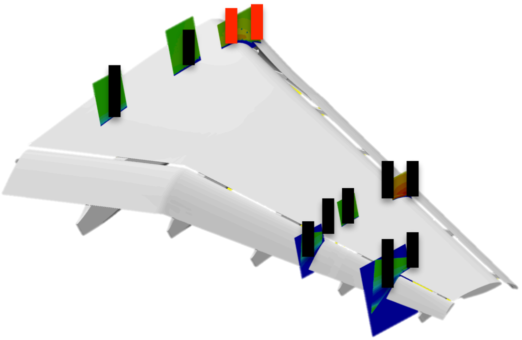
- k-ω for VGIRD grid begin to show a loss of lift

Case 2a Velocity Profile Results, Alpha 7°



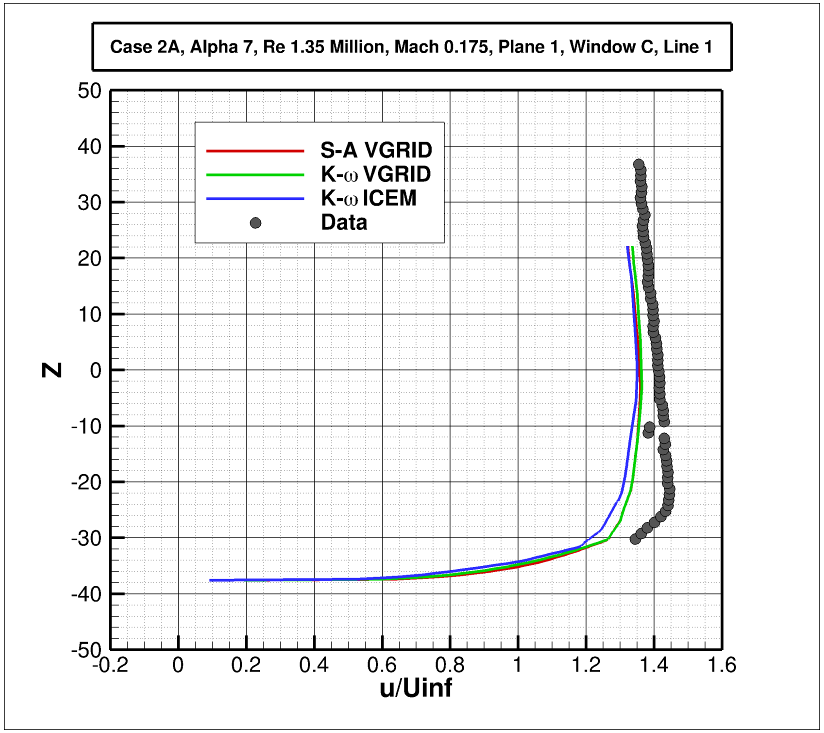


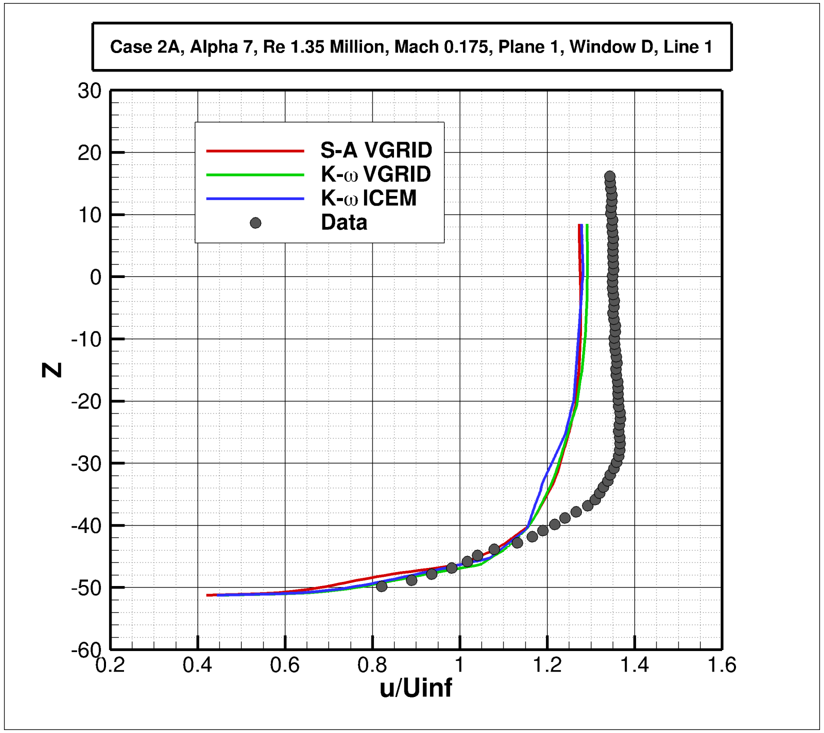
- Computational data compares well with experimental data



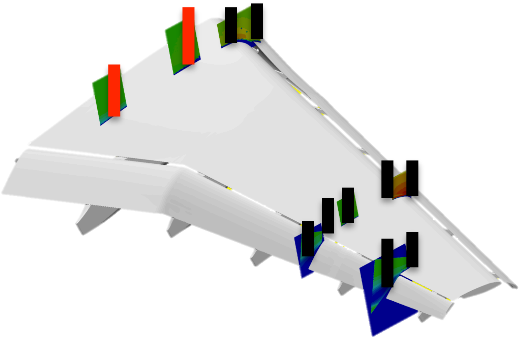
- Computational data trends similar to each other, and data scattered within the minimum and maximum

Case 2a Velocity Profile Results, Alpha 7°

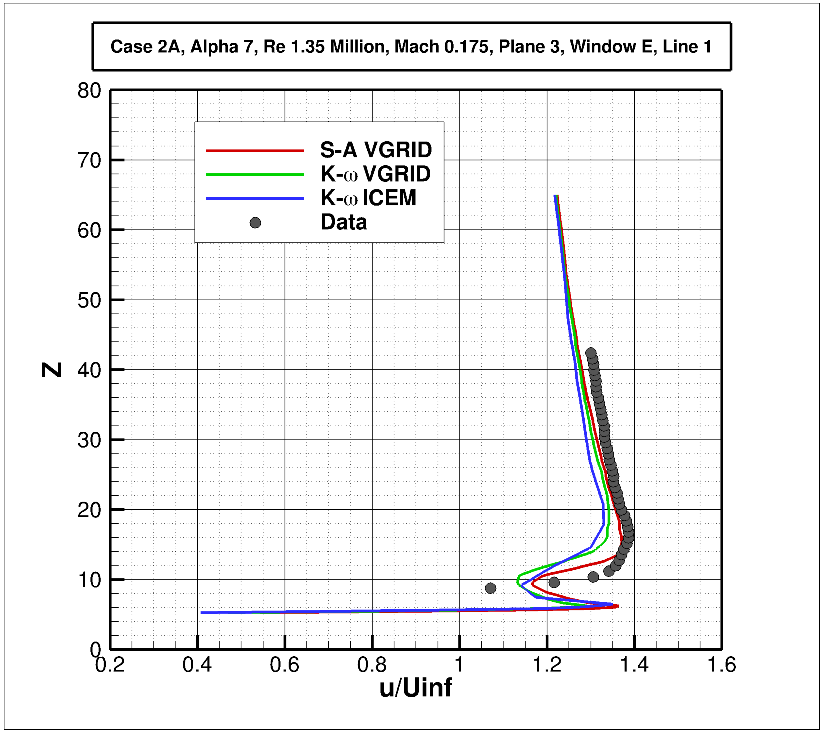


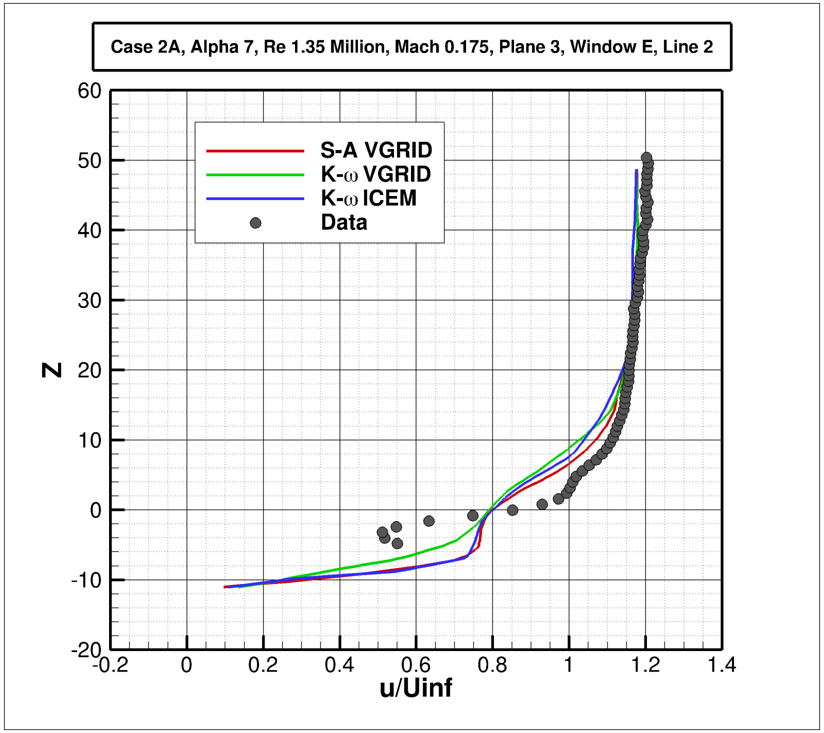


- Computational data trends similar to experimental, but off in magnitude

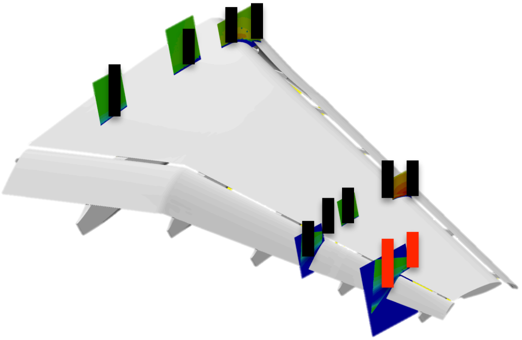


Case 2a Velocity Profile Results, Alpha 7°



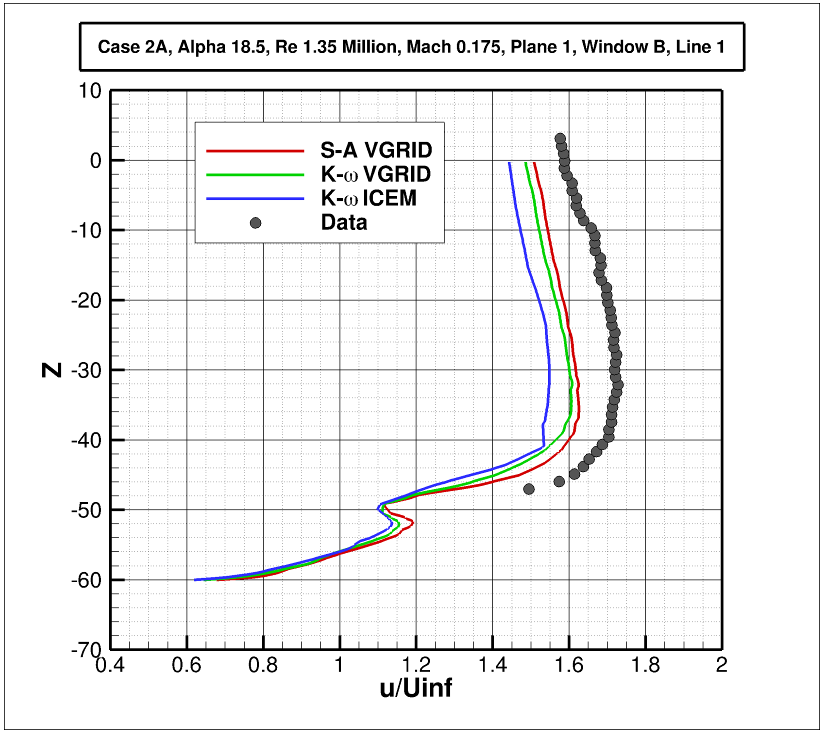


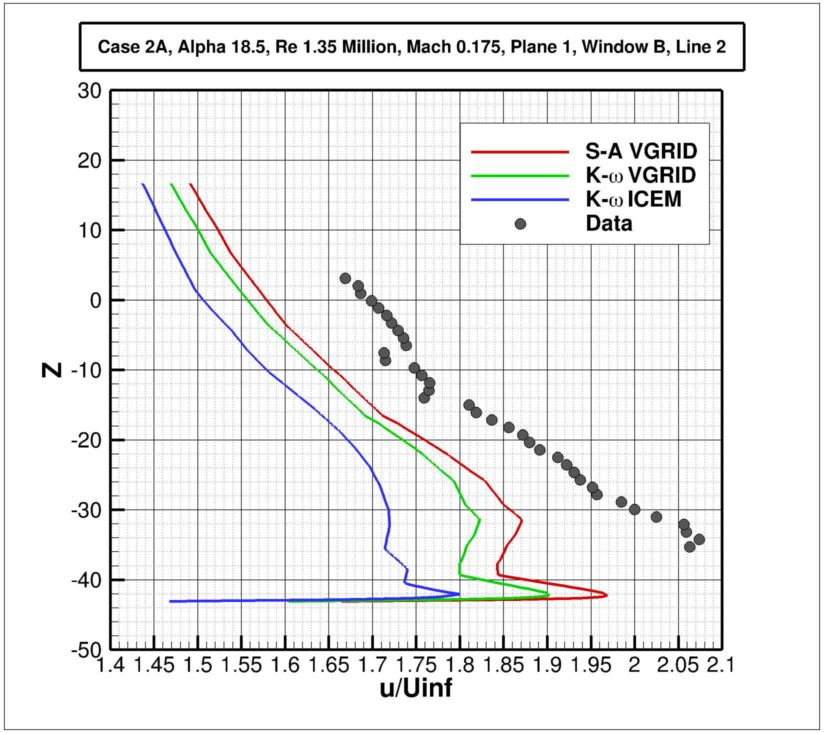
- Computational data compares well with experimental data



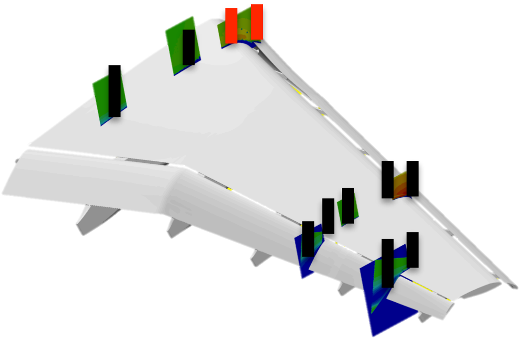
- Poor capture of upstream wake

Case 2a Velocity Profile Results, Alpha 18.5°

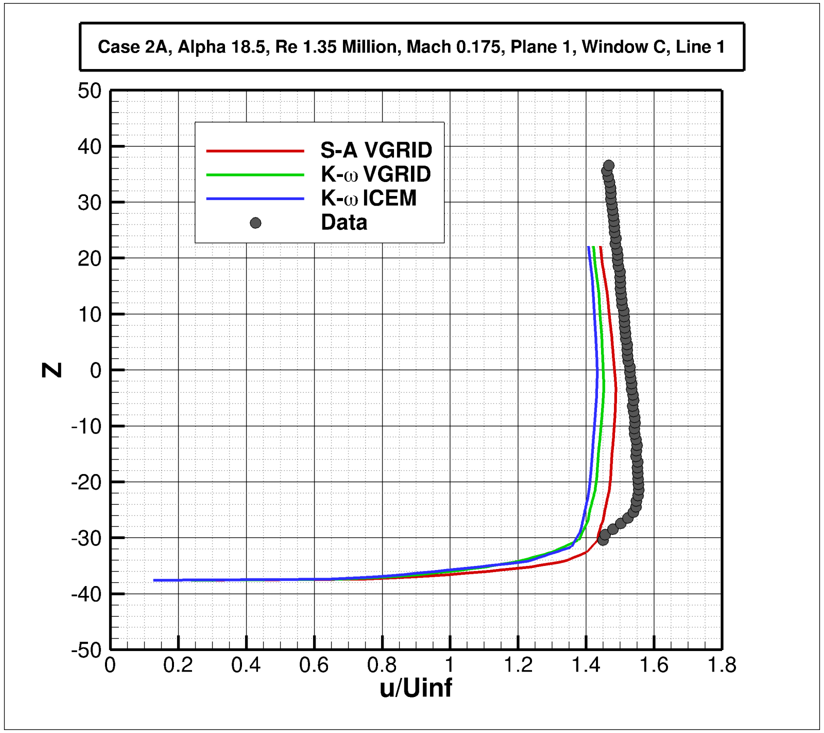


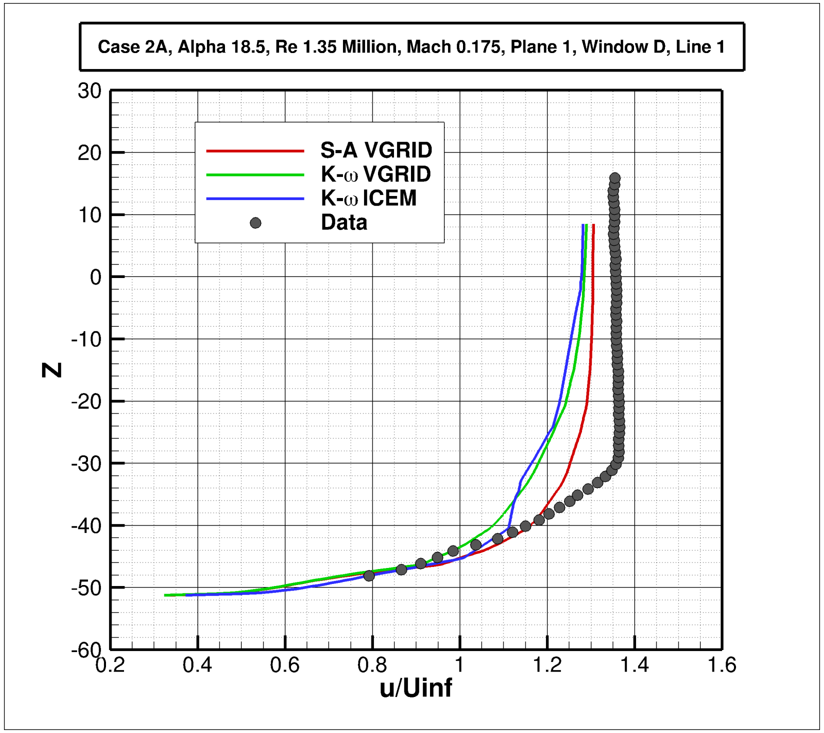


- Computational data trends similar to experimental, but off in magnitude

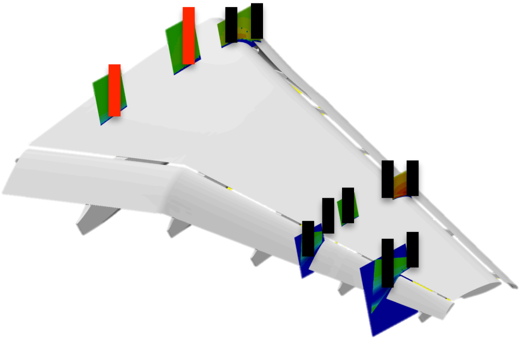


Case 2a Velocity Profile Results, Alpha 18.5°

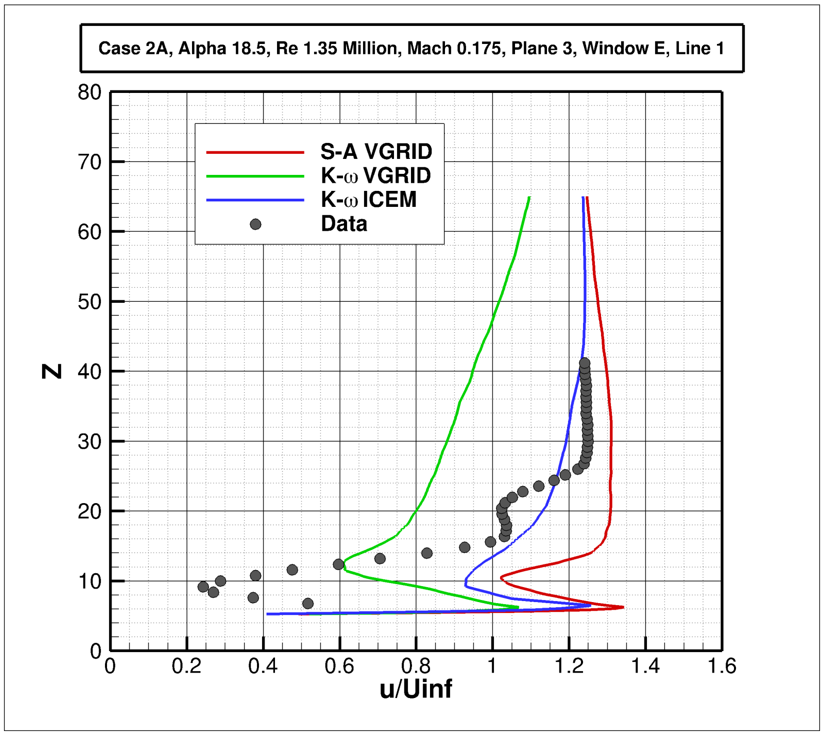


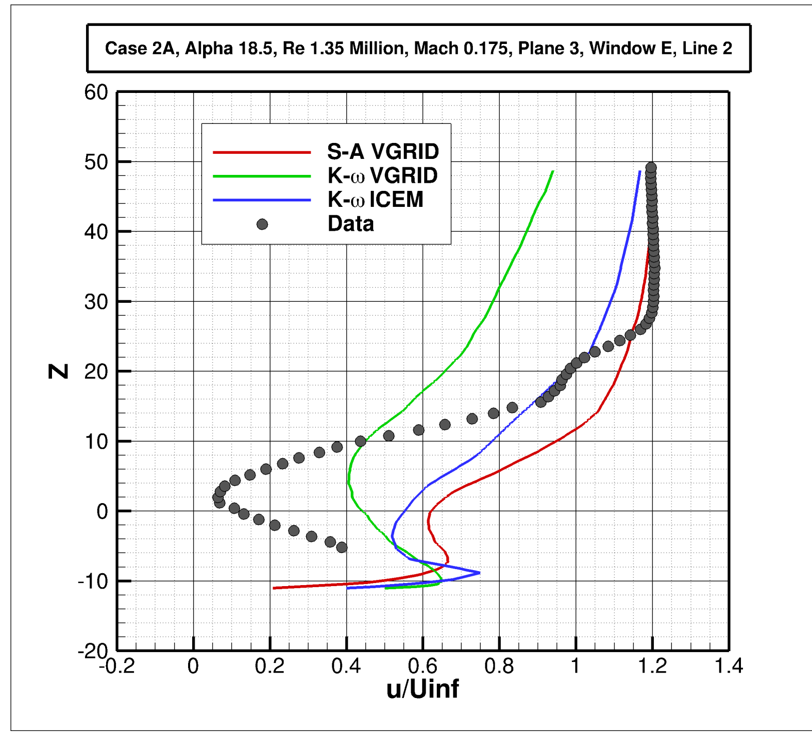


- Computational data trends similar to experimental, but off in magnitude

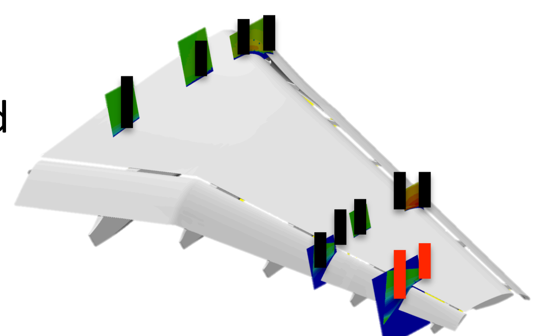


Case 2a Velocity Profile Results, Alpha 18.5°





- Agreement degrades with experimental data at outboard stations for higher angle of attack, due to unrefined wake interaction

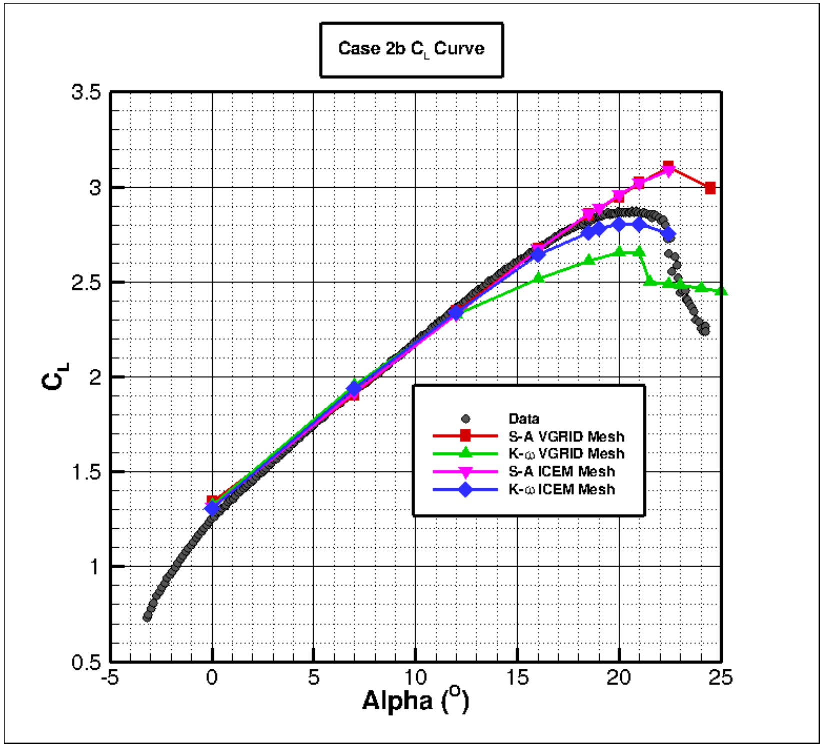


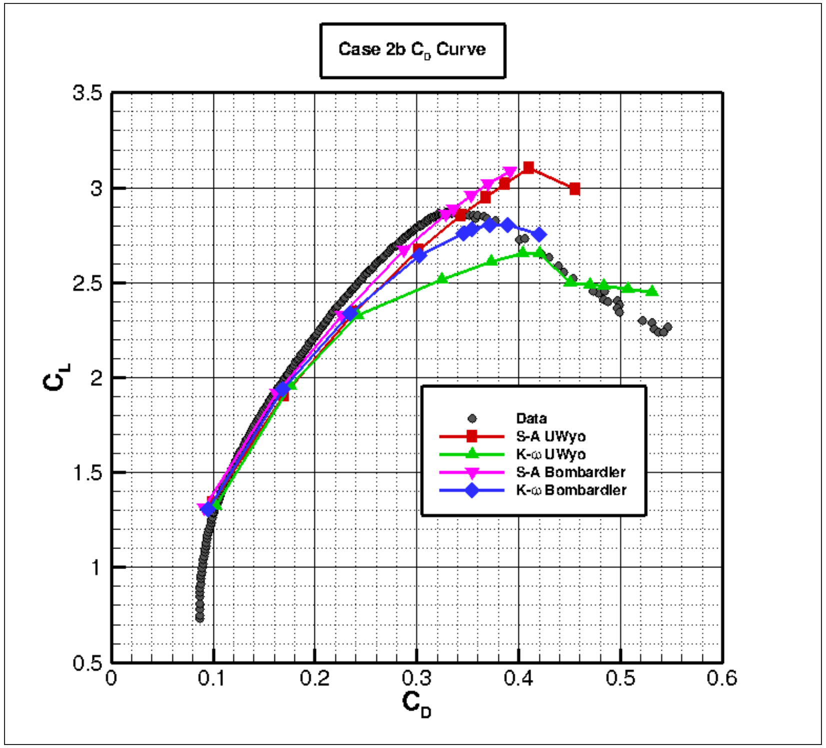
- k-ω on the VGRID grid differs increasingly from other two solutions

Case 2b

- Mach Number = 0.175
- Reynolds Number = **15.1** million based on MAC
- Angle of Attack = 0°, 7°, 12°, 16°, 18.5°, 20°, 21°, 21.5°, 22.4°, 23°, 24°, and 25°
- Grids
  - VGRID
    - S-A and k-ω
  - ICEM-TETRA
    - S-A and k-ω

Case 2b Polars Results

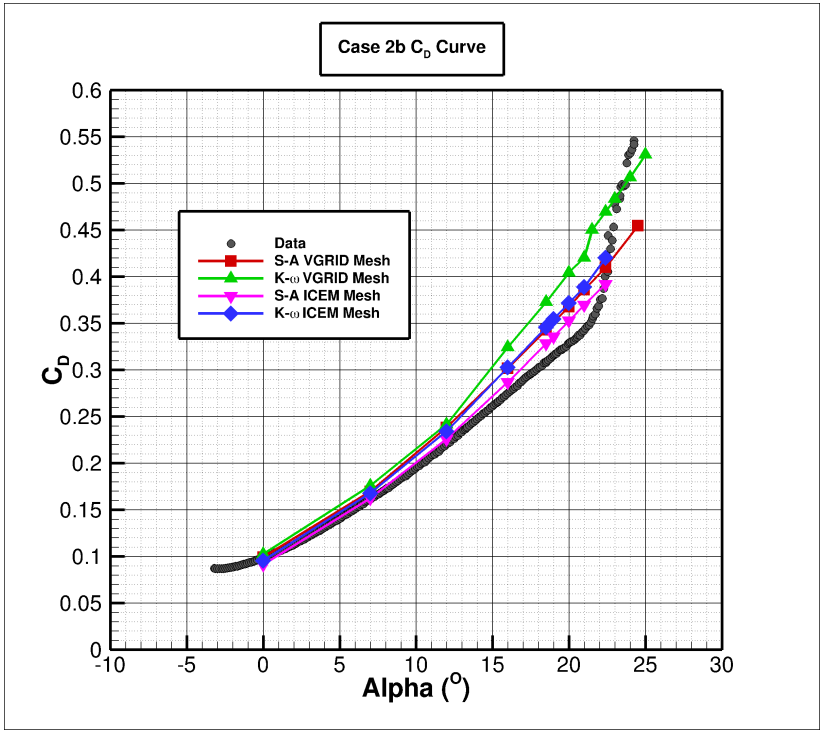


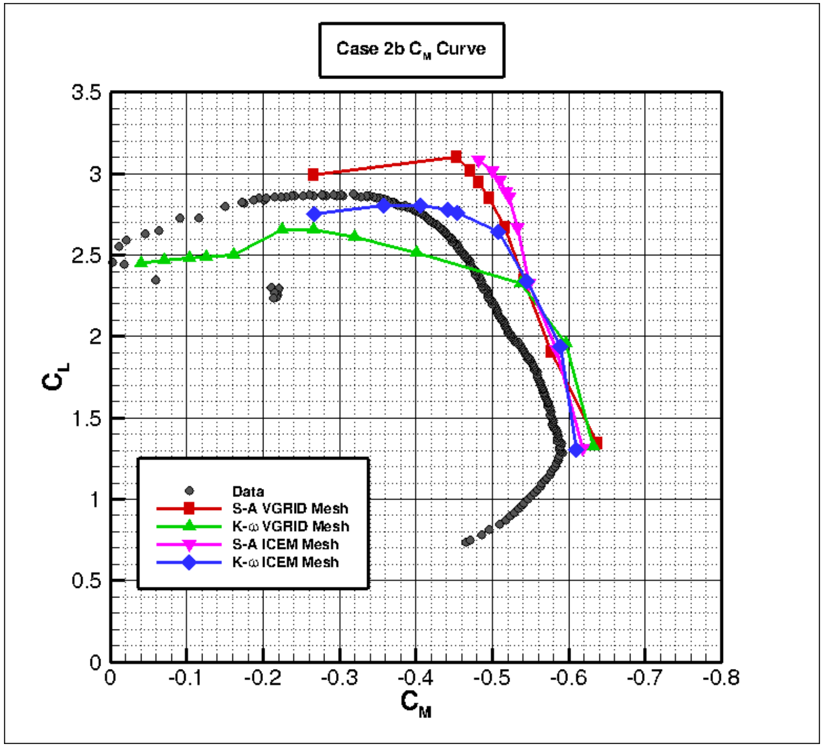


- Linear region well predicted
- k-ω on the ICEM grid predicts stall best
- k-ω on the VGRID grid underpredicts C_{LMAX}
  - Stall incidence well predicted

- S-A overpredicts C_{LMAX} and incidence
- S-A results agree well on both grids
- K-ω results differ near stall on both grids

Case 2b Polars Results

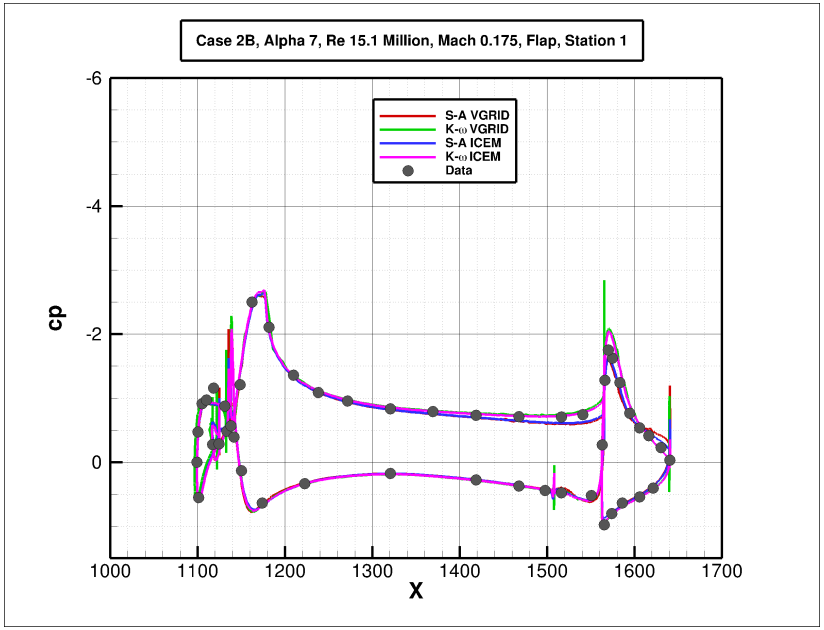


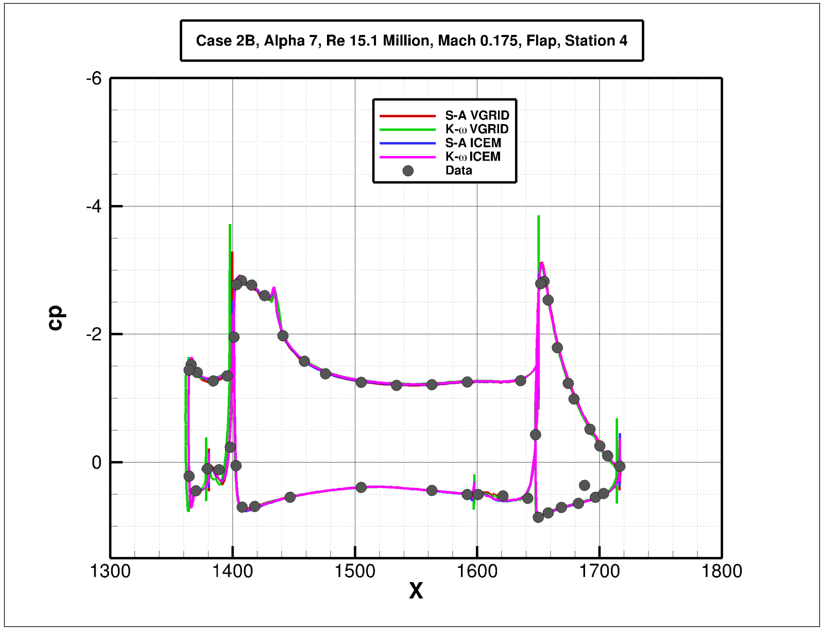


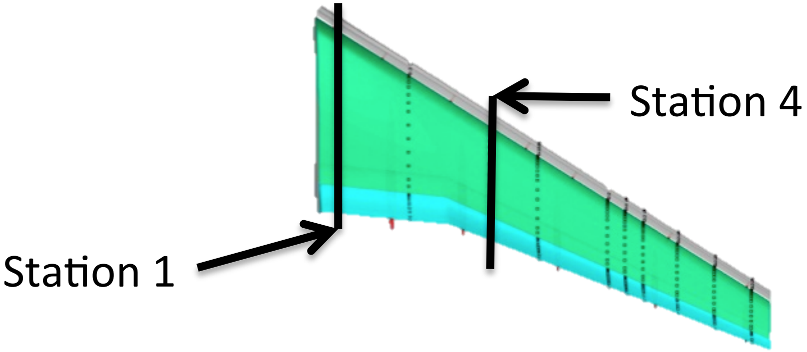
- Higher drag is predicted by k-ω VGRID grid
- Remaining results slightly overpredict CD versus incidence

- Poorer agreement for computed CM with experimental data
    - Best trend obtained with k-ω on ICEM mesh

Case 2b C_P Results, Alpha 7°

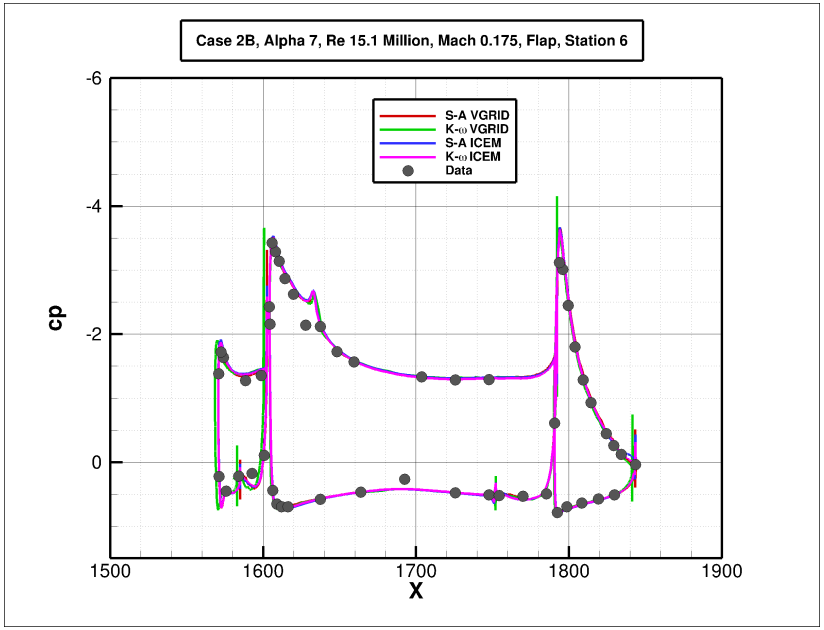


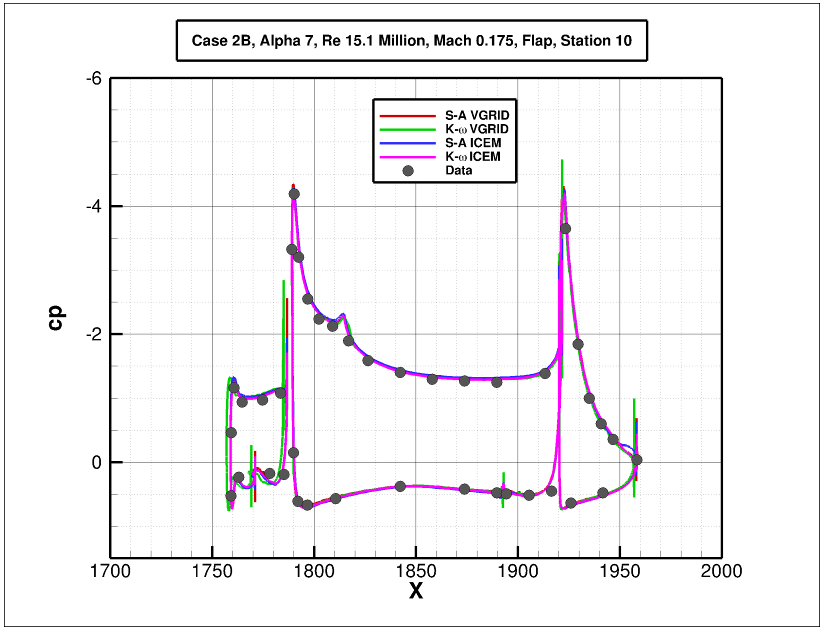


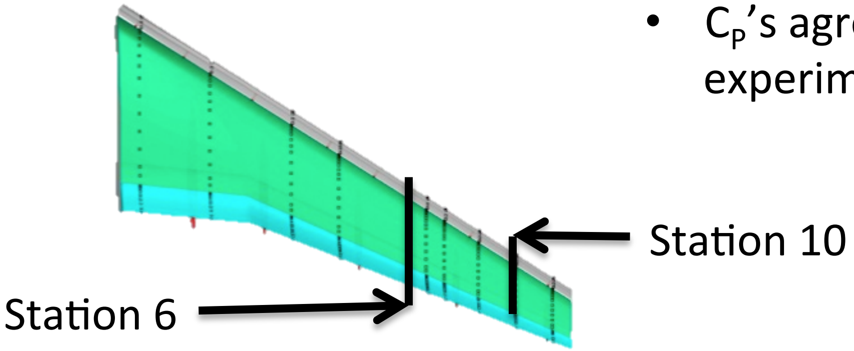


- C_P's agree well with experimental data

Case 2b C_P Results, Alpha 7°

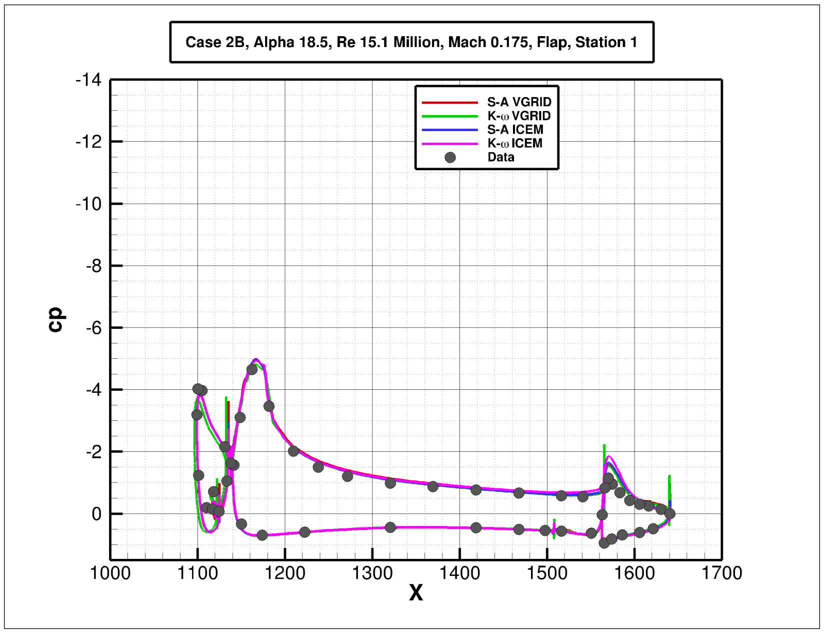


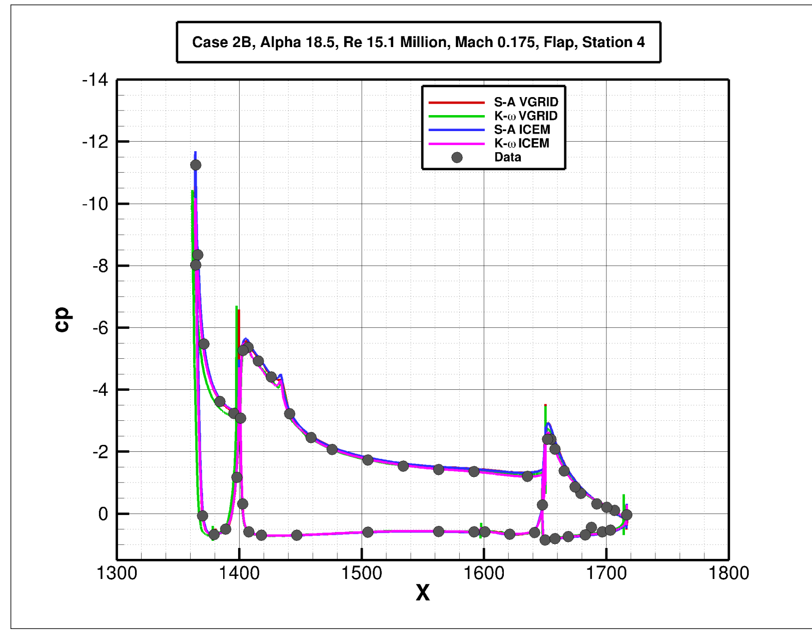


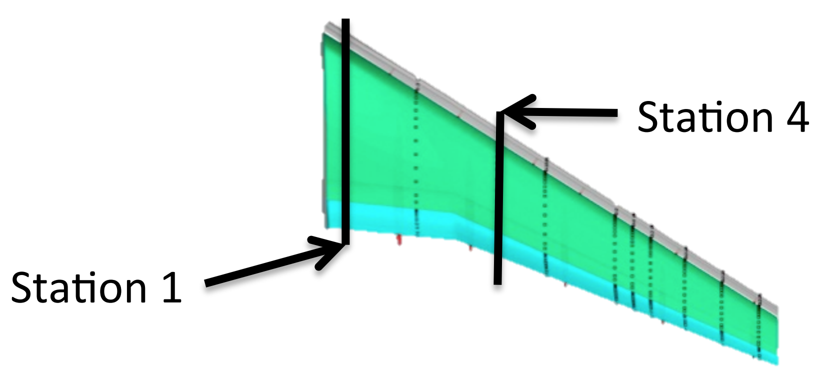


- C_P's agree well with experimental data

Case 2b C_P Results, Alpha 18.5°

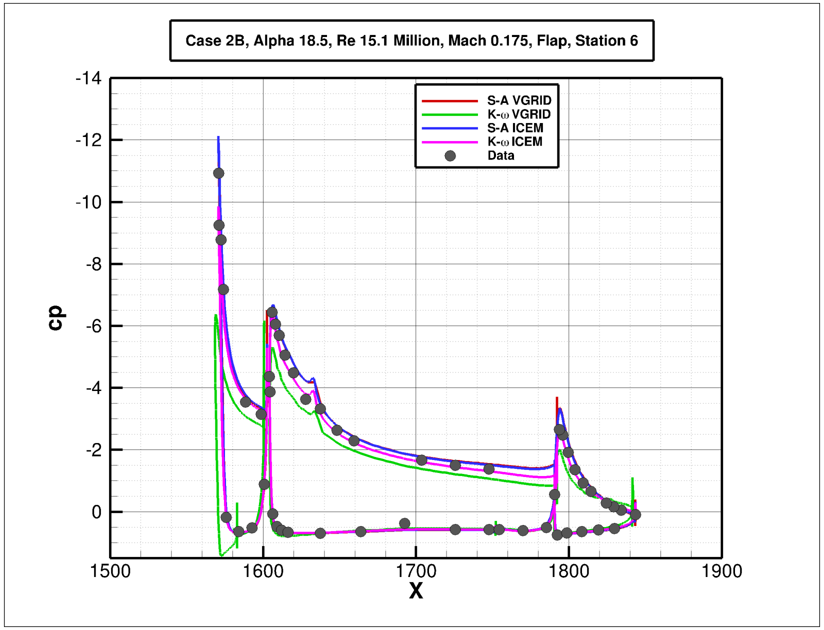


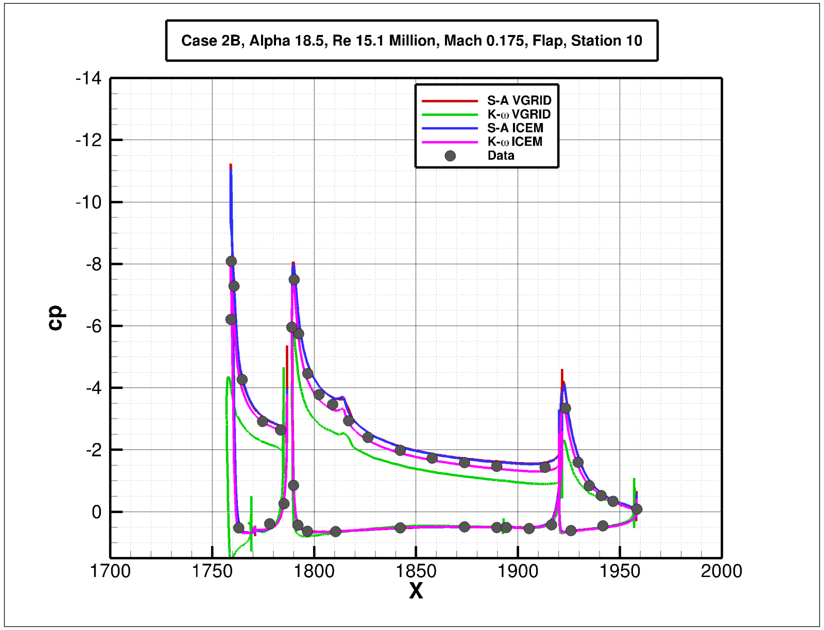




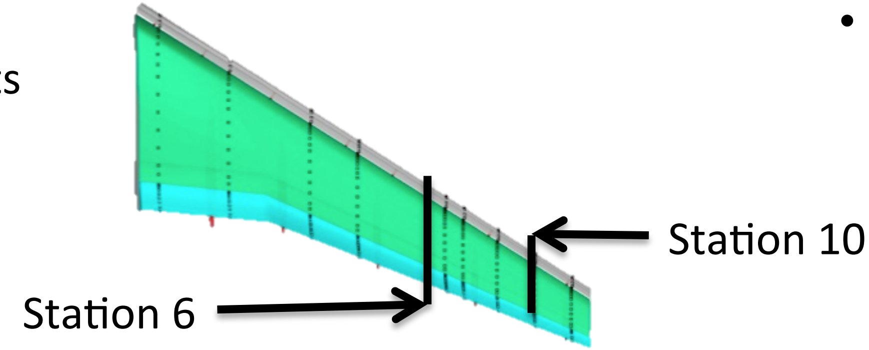
- C_P's agree well with experimental data

Case 2b C_P Results, Alpha 18.5°



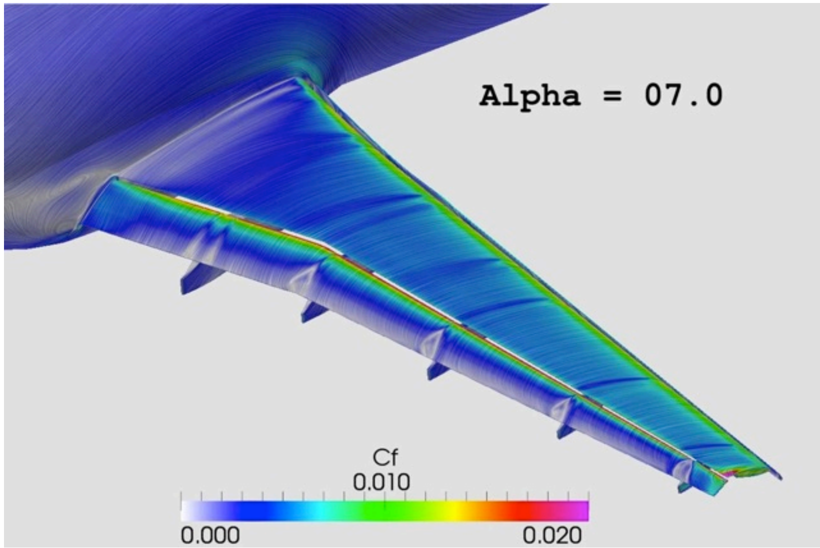


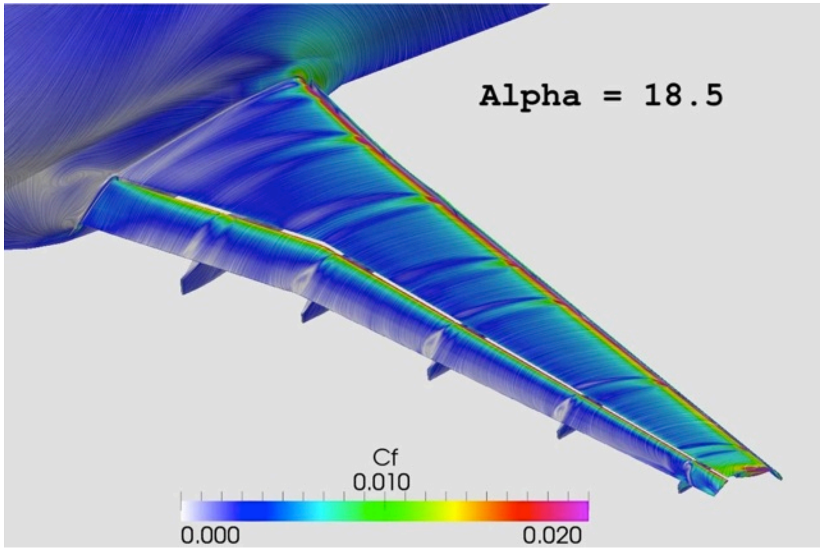
- k-ω on the VGRID grid differs from other results at higher angle of attack
- k-ω on the VGRID grid shows a loss of lift



- Agreement with experimental data degrades at outboard stations for higher angle of attack

Case 2b Surface Oil Flows

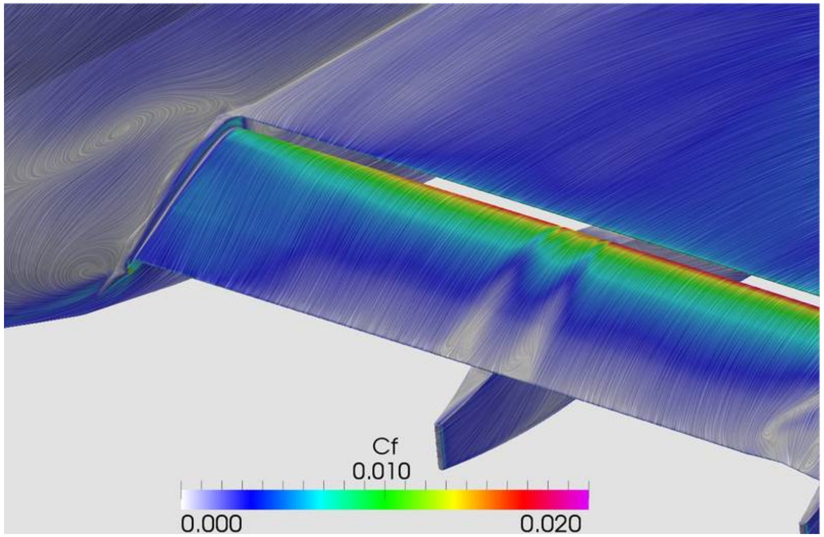


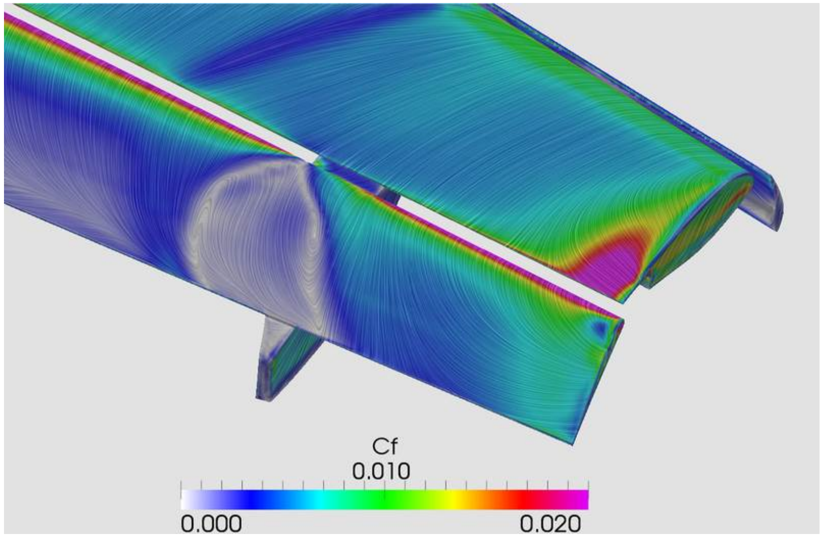


- Flow separation behind fairings prior to stall

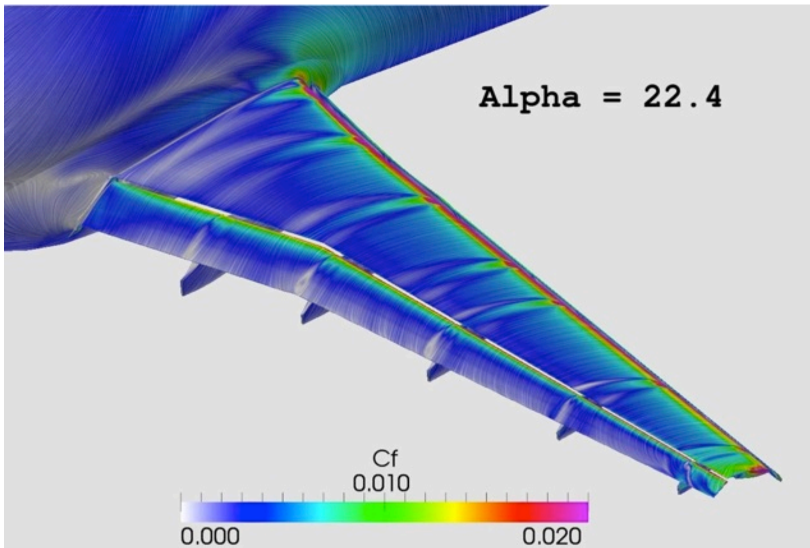
- Flow separation behind fairings prior to stall

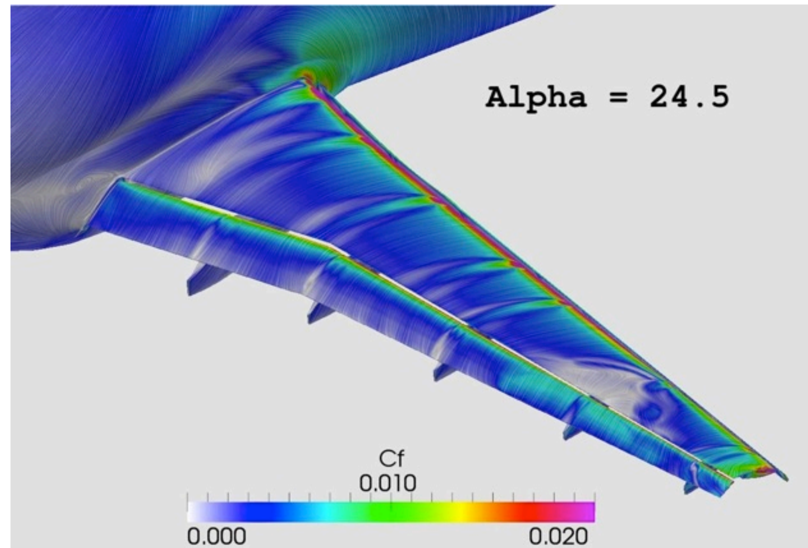
Case 2b Surface Oil Flows





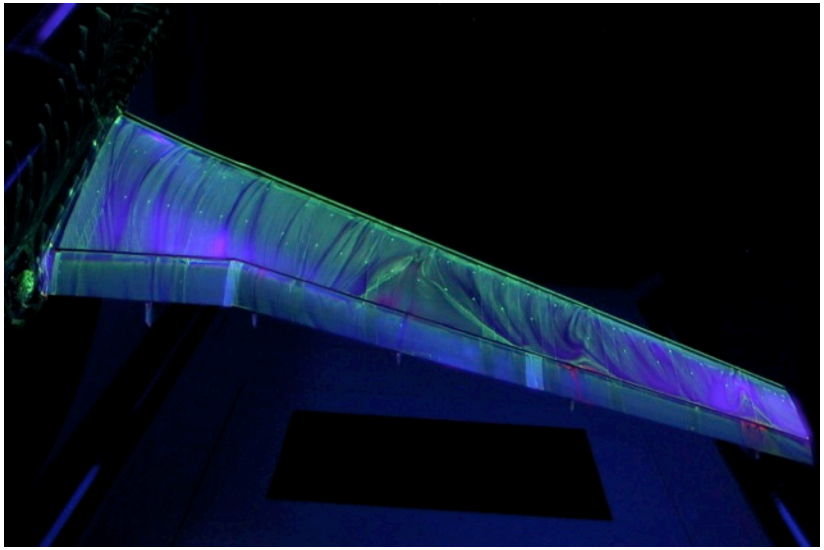
Case 2b Surface Oil Flows

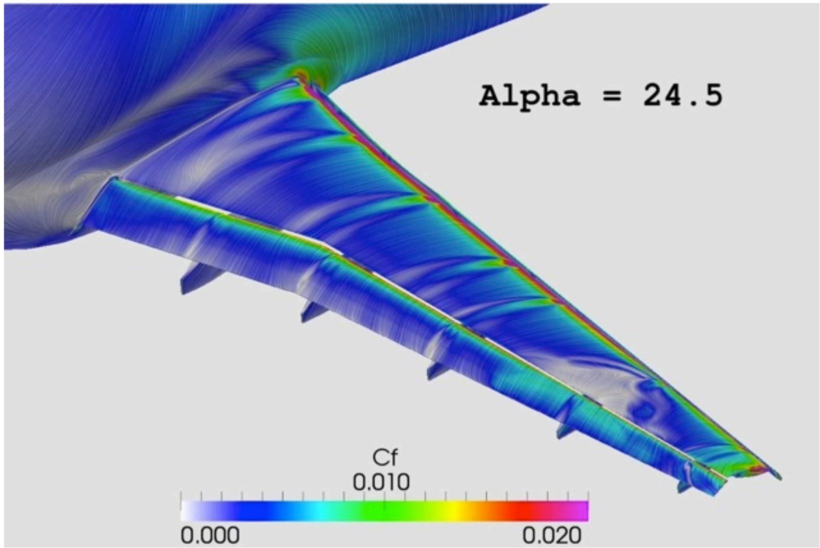




- Flow separation behind fairings prior to stall
- Complete stall chordwise at the outboard flap track

Case 2b Surface Oil Flows





- Complete stall chordwise the middle flap track*

*Image for case2a

- Complete stall chordwise at the outboard flap track

Conclusions

- S-A tends to over predict C_{LMAX} in both location and value
- k-ω tends to under predict C_{LMAX} value, but provides a better prediction of stall incidence
- k-ω on the ICEM mesh predicts the forces and moments most closely to the experimental data (Bombardier)
- k-ω results differ more across grid type than S-A
  - This may be due to increased presence of flow separation in the k-ω model rather than increased sensitivity to mesh resolution
- Principle grid differences
  - VGRID includes spanwise stretching
    - Higher resolution in leading/trailing edge regions
  - ICEM results in increased mesh resolution in mid chord regions
  - ICEM meshes have slower normal growth in BL regions near wall
  - VGRID has slower growth/smoother transition at edge of BL

Conclusions

- C_P's and velocities are predicted better at lower angles of attack and inboard stations than at higher angles of attack and outboard stations
- Force, moment, surface C_P, and velocity profiles are consistent across the different models and grids
  - Close inspection of the differences could not conclusively demonstrate better agreement with one particular model or another compared to the experimental data
- Stall mechanism is show to be driven by the flap track fairings, both experimentally and computationally
  - The specific flow separation pattern is different computationally, in these results as well as most other workshop results, when compared to the experimental data

Further Work

- Additional grid convergence for the Case 2 model to be able to compare to experimental data
- Case 3 studies
- Increased robustness from the the addition of the GMRES solver for at and near stall

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